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RPV FLYING QUALITIES DESIGN CRITERIA

ROCKWELL INTERNATIONAL CORPORATION
MISSILE SYSTEMS DIVISION
COLUMBUS, OHIO 43216

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Final Report for Period January 1976 – December 1976

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This technical report has been reviewed and is approved for publication.

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FOR THE COMMANDER

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The concept and philosophy for the organization of an RPV Flying Qualities Design Criteria are presented in a preliminary framework of criteria with supporting background and rationale. This report completes Phase II of a four-phase AFFDL/FGC program for the development of an RPV Flying Qualities Specification. The performance-oriented criteria are developed in hierarchical fashion from mission requirements, through total system requirements, to subsystem requirements. The criteria encompass automatic and manual controls, command and data link, controls and displays as well as vehicle stability and

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20. ABSTRACT

control. The material was based on an RPV literature search and reveiw,and an evaluation of existing military specifications for piloted aircraft, such as MIL-F-8785B, MIL-F-83300, MIL-F-9490D (USAF), and MIL-C-18244A (Navy).

PREFACE

This report was prepared by the Missile Systems Division (MSD) of Rockwell International Corporation, P. O. Box 1259, Columbus, Ohio 43216, under USAF Contract F33615-75-C-3159, "RPV Flying Qualities Design Criteria Study". The contract was initiated under Project 8219: Remotely Piloted Vehicle (RPV) Flying Qualities Design Criteria Study.

The program was administered under the direction of the Air Force Flight Dynamics Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. Mr. Terry L. Neighbor of AFFDL/FGC was project engineer. The prime investigators for Rockwell International Corporation were Charles F. Prosser of the Missile Systems Division and Curtiss D. Wiler of the Los Angeles Aircraft Division.

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REQUEST FOR COMMENTS

This document presents an initial organization and structure for the RPV Flying Qualities Criteria. It is requested that comments on this document be forwarded to:

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbols

h_{max}	- maximum service altitude
$h_{o_{max}}$	- maximum operational altitude
$h_{o_{min}}$	- minimum operational altitude
H_z	- Hertz
c.g.	- vehicle center of gravity
M	- Mach number
V	- airspeed (where appropriate, V may be replaced by M)
V_S	- Stall Speed
$V_S(X)$, $V_{min}(X)$, $V_{max}(X)$	- short-hand notation for the speeds V_S, V_{min}, V_{max} for a given configuration, weight, center-of-gravity position, and external store combination associated with Flight Phase X. For example, the designation $V_{max}(TO)$ is V_{max} for the configuration associated with the takeoff Flight Phase.
V_{trim}	- trim speed
V_{end}	- speed for maximum endurance
$V_{L/D}$	- speed for maximum lift-to-drag ratio
$V_{R/C}$	- speed for maximum rate of climb
V_{range}	- speed for maximum range in zero wind conditions
V_{NRT}	- high speed, level flight, normal rated thrust
V_{MRT}	- high speed, level flight, military rated thrust
V_{MAT}	- high speed, level flight, maximum augmented thrust
V_{max}	- maximum service speed
V_{min}	- minimum service speed
$V_{o_{max}}$	- maximum operational speed
$V_{o_{min}}$	- minimum operational speed

Symbols

τ_R	- first order roll mode time constant, positive for stable mode
ω_{n_d}	- undamped natural frequency of the Dutch roll oscillation
ϕ_t	- bank angle change in time t, in response to control deflection
$\frac{p_{osc}}{p_{avg}}$	- a measure of the ratio of the oscillatory component of roll rate to the average component of roll rate following a rudder-pedals-free step aileron control command.
$\measuredangle \frac{p}{\beta}$	- phase angle between roll rate and sideslip in the free Dutch roll oscillation. Angle is positive when p leads β
$\left\| \frac{\phi}{\beta} \right\|_{\alpha}$	- at any instant, the ratio of amplitudes of the bank-angle and sideslip-angle envelope in the Dutch roll mode
ψ_g	- Actual vehicle ground track direction
ζ_{sp}	- damping ratio of the short-period oscillation
$\omega_{n_{sp}}$	- undamped natural frequency of the short-period oscillation
ζ_p	- damping ratio of the phugoid oscillation
ω_{n_p}	- undamped natural frequency of the phugoid oscillation
n	- normal acceleration or normal load factor, measured at the c.g.
n_L	- symmetrical flight limit load factor for a given Vehicle Normal State, based on structural considerations
n_{max}, n_{min}	- maximum and minimum Service load factors
n(+), n(-)	- for a given altitude, the upper and lower boundaries of n in the V-n diagrams depicting the Service Flight Envelope
$n_{o_{max}}, n_{o_{min}}$	- maximum and minimum Operational load factors

Symbols

$n_o(+)$, $n_o(-)$	- for a given altitude, the upper and lower boundaries of n in the V-n diagrams depicting the Operational Flight Envelope
n/α	- the steady-state normal acceleration change per unit change in angle of attack for an incremental elevator defelction at constant speed (airspeed and Mach number)

Abbreviations

AFCS	- Automatic Flight Control System
AGL	- Above Ground Level
ARPV	- Advanced Remotely Piloted Vehicle
CSAS	- Control Stability Augmentation System
C.G.	- Center of Gravity
DCDRS	- Drone Control and Data Retrieval System
E.O.	- Electro Optical
ETA	- Estimated Time of Arrival
FCS	- Flight Control System
GPS	- Global Positioning System
HALE	- High Altitude Long Endurance
NRT	- Normal rated thrust, which is the maximum thrust at which the engine can be operated continuously
MRT	- Military rated thrust, which is the maximum thrust at which the engine can be operated for a specified period.
MAT	- Maximum augmented thrust: maximum thrust, augmented by all means available for the Flight Phase
MSL	- Mean Sea Level
PME	- Prime Mission Equipment
RMS	- Root Mean Square

Abbreviations

RPV	- Remotely Piloted Vehicle
TAS	- True Air Speed
TO	- Take Off
TOA	- Time Of Arrival
VOR	- Very High Frequency Omni Directional Range
V/STOL	- Vertical/Short Take Off and Landing

SECTION I

INTRODUCTION

Section I of this document is intended to explain the concept and philosophy associated with the organization and structure of the RPV Flying Qualities Criteria. Section II presents the framework of the preliminary flying qualities criteria with supporting background and rationale.

The material presented in Section II is based on an RPV literature search and review (Reference 1), and a critical evaluation of existing military specifications for piloted aircraft, such as MIL-F-8785B, MIL-F-83300, MIL-F-9490D (USAF), and MIL-C-18244A (Navy). Section II presents the criteria, paragraph by paragraph, in the order of the selected outline using a format similar to the background documents for the flying qualities specifications of piloted aircraft (References 2 and 3). It also incorporates some applicable wording from these sources. The proposed criteria are presented in the form of requirements or sets of requirements followed by discussions of the intent, rationale, or background data upon which the criteria are based.

This study effort represents Phase II of a long-range four-phase AFFDL/FGC program plan (Reference 4) for the development of an RPV Flying Qualities Specification. The objective of this phase was to develop a preliminary framework for RPV flying qualities criteria which would be expanded, refined, and validated by simulation and analysis in Phase III. This would then be followed by a government development of an RPV flying qualities specification in Phase IV.

1. PHILOSOPHY/STRUCTURING OF CRITERIA

In studying RPV flying qualities, the total RPV system must be considered. This includes not only vehicle stability and control, but must also encompass automatic and manual control, command and data link, and the man-machine interfaces (i.e., display information and controls) which directly affect the flying qualities of the RPV.

The principal topics and structure of the RPV flying qualities criteria are shown in Figure 1. The first level, corresponding to the standard breakdown used in military specifications, includes scope, classifications, applicable documents, quality assurance, preparation for delivery, and notes as well as flying qualities requirements. The main effort of this study was directed at Section 1-Scope and Classifications, and Section 3-Requirements. Sections 2, 4, 5 and 6 (designated by dashed blocks in Figure 1) were not specifically addressed in this initial development of the RPV Flying Qualities Design Criteria, and are not treated in this document.

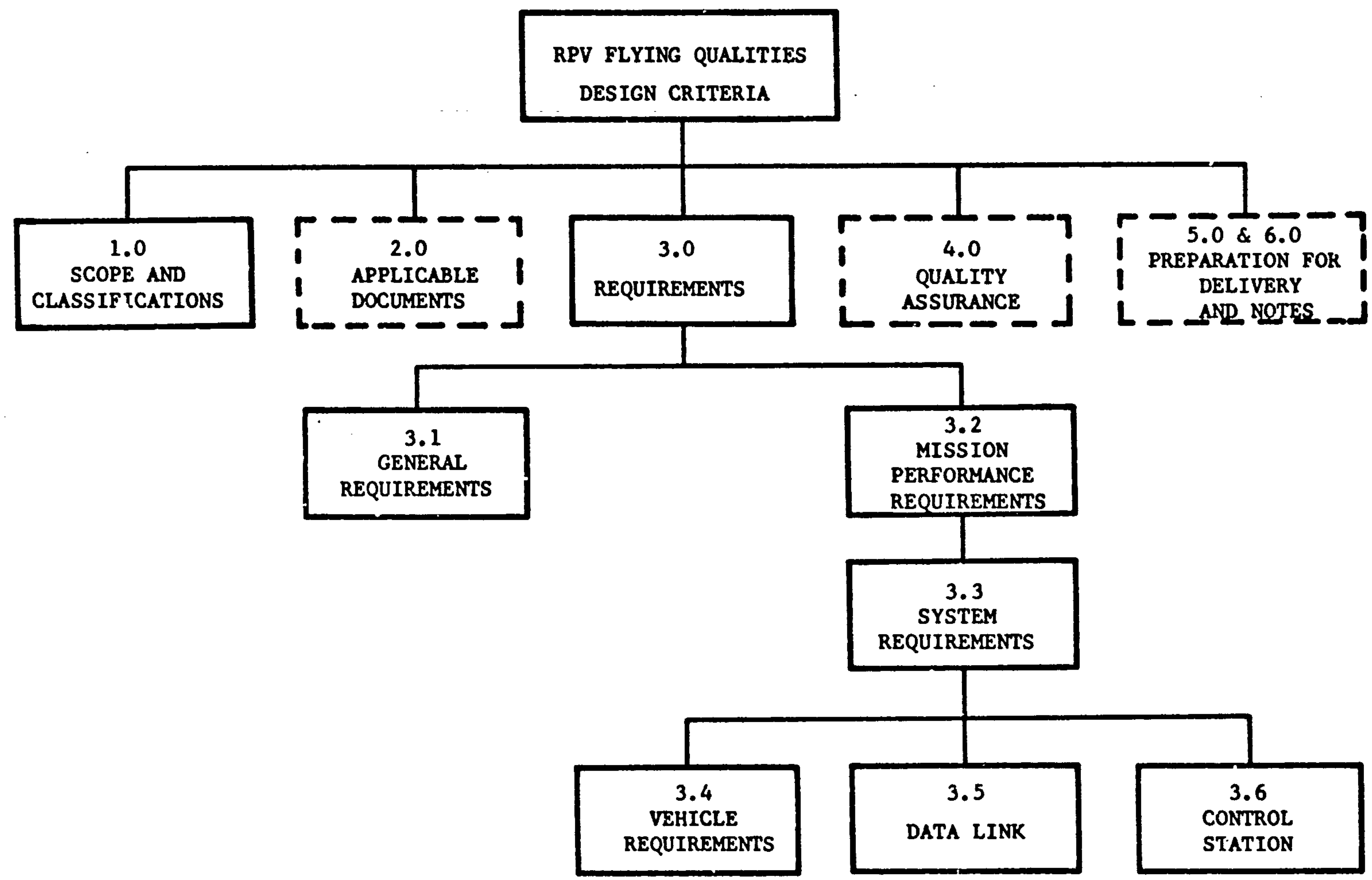


Figure 1. Organization and Hierarchy of RPV Flying Qualities Criteria

1.1 Scope and Classifications

The general organization of the Scope and Classification Section is similar in structure to MIL-F-8785B and establishes a framework which permits the tailoring of each requirement according to: vehicle class, flight phase category, flight control mechanization (automatic or manual), and flying quality level which relates to the ability of performing the operational mission.

The principal differences in the RPV classification structure, from that of MIL-F-8785B, are the use of four flight phase categories instead of three, and the application of flying quality levels to both automatic and manual control. A more detailed discussion of the rational for this framework is given in the Statement and Discussion of Requirements (Section II).

The scope of the present document is restricted to the more conventional airplane-type RPV configurations. During the study, V/STOL criteria were initially included in several of the sections; however, it became apparent that a complete treatment of the V/STOL criteria only complicated the basic text and detracted from the effort devoted to structuring the basic criteria. It is believed that the RPV V/STOL criteria can best be addressed as an addendum to the basic criteria wherein appropriate sections are modified, deleted, or replaced.

1.2 Requirements

As shown in Figure 1, the requirements section of the RPV flying qualities criteria is subdivided in six major subdivisions. The general requirements, Section 3.1, specify the conditions under which the RPV requirements are to be applied. This section is similar in organization to that of MIL-F-8785B. The RPV conditions are defined in terms of: Operational mission(s) - intended use; vehicle states identified by weight, center-of-gravity envelopes, external stores, flight phase configurations, and operational status; and vehicle flight envelopes.

The organization and philosophy of the remaining five subsections (3.2 thru 3.6) represent a significant variation and expansion from present manned aircraft flying qualities specifications. For piloted aircraft, automatic and manual flight control requirements are covered by several specifications. The types of requirement for manual and automatic flight control tend to differ. Many automatic control requirements are stated in terms of closed-loop performance or accuracy requirements for a guidance or flight control parameter. However, the manual control flying qualities requirements tend to be more directly related to vehicle and flight control response characteristics which the pilot needs and likes to do the job. The flying qualities levels are directly associated with a 'pilot rating scale' which reflects how hard he has to work to do the task. Although performance is implied, present

flying qualities specifications for piloted aircraft are not stated in terms of the actual mission flight phase performance of the closed-loop pilot-vehicle combination. (Herein "performance" is used in the broad sense rather than to denote the traditional aerodynamic performance parameters related to thrust and drag.)

The organization for the RPV flying qualities requirements presented herein is a requirement hierachy which includes mission performance, system, and subsystem requirements. For manned aircraft, pilot safety is an important consideration; for RPV's this is not the case. Except for obvious priorities on vehicle recoverability, reliability, and personnel safety (launch, recovery, and test areas), the main consideration for RPV requirements is directed at performance requirements. Sections 3.2 thru 3.6 have been organized in order of precedence starting with mission performance requirements and progressing down through system and subsystem level requirements. The relationships of these sections are depicted in Figure 2. In summary, Section 3.2 defines overall operational performance requirements which the RPV system must be capable of providing in order to accomplish the various mission flight phase tasks. Section 3.3 identifies more detailed total system level requirements for various automatic and manual flight control functions, and operational characteristics. These system requirements include the combined operational characteristics and interfaces of vehicle, data link and control station. Sections 3.4, 3.5, and 3.6 divide the RPV system into three major subsystem areas and identify related subsystem requirements.

The mission performance section (3.2) specifies operational performance requirements at the mission level, and where feasible, identifies pertinent performance variables and ranges of values required to successfully accomplish the mission flight phases. Since these are mission requirements, they apply to both automatic and manual control mechanizations, or any integrated combination of both. The intent of these requirements is to serve the following purposes:

(a) Identify performance values and/or parameters which the procuring activity must consider when defining the performance requirements for the particular RPV system being designed.

(b) Provide a mission flight phase framework which the procuring activity can use to specify performance for a particular RPV design. The procuring activity will clearly identify within this framework what performance requirements of this specifications, the vehicle specification, or other related system performance specification are to be used.

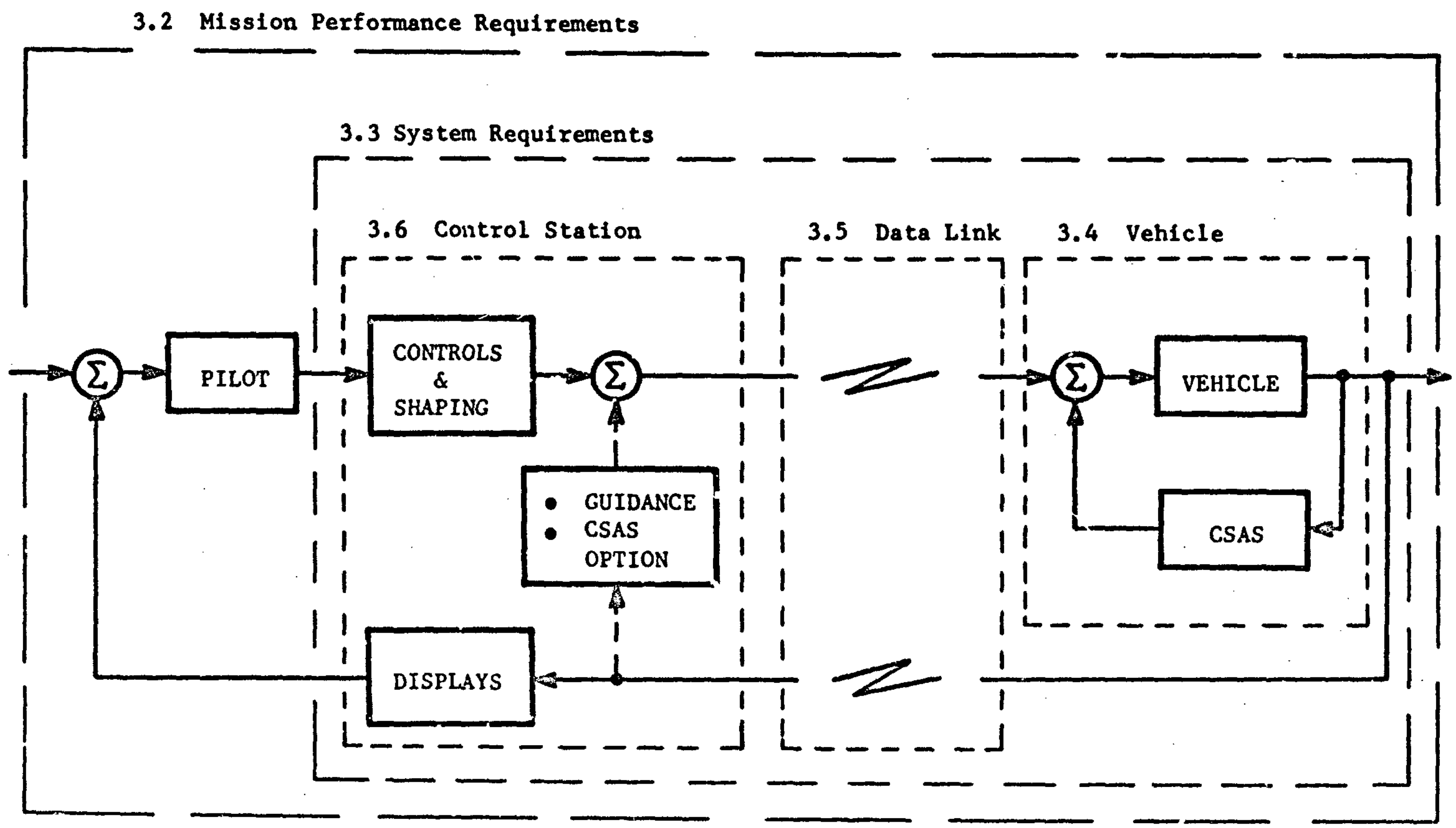


Figure 2. RPV Flying Qualities Criteria Subdivision.

(c) Provide requirements precedence. The mission requirements of Section 3.2 represents the highest level in the requirement hierarchy. When performance has been adequately established or demonstrated, but some related system system requirements in Sections 3.3 through 3.6 remains in question, the latter requirement may be relaxed through agreement by the procuring activity.

The latter philosophy arises from indications that present aircraft specifications have, at times, caused sacrifices in performance only for the sake of meeting a particular requirement. The RPV specification should, of course, contain consistent requirements at the total system and subsystem levels: however, it is impossible to account for all peculiarities that may arise when considering all possible combinations of missions, methods of control, vehicle configurations, etc.

Section 3.3, the system flying qualities requirements, treats the combined operational characteristics of vehicle, data link and control station as seen by the operator. There are obviously a number of variations and options in control loop closures which are not shown in Figure 2. For instance the principal vehicle augmentation may be located on the ground, with a minimum of equipment aboard the vehicle to insure reasonable behavior during intermittent loss of data link. Navigation and guidance may be performed on the vehicle or on the ground. Navigation updating may be accomplished through the operator or ground computers, or directly on the vehicle using systems such as LORAN or Global Positioning Satellites (GPS). The requirements of Section 3.3 deal only with the total system functional requirement and do not distinguish among the many methods of implementation. These system requirements are organized under five major topics: Automatic Control, Manual Control, Stability Margins, Operation and Interface, and Atmospheric Disturbances. In general, the automatic control requirements deal with performance of various flight control and guidance functions. The manual flying qualities are directly associated with total system response characteristics which the operator requires to do the job. The manual flying qualities levels are directly associated with a 'pilot rating scale' which in turn, is used to establish acceptable parameter ranges for each of the three flying quality levels.

Sections 3.4, 3.5 and 3.6 specify the additional subsystem requirements which are specifically required of the vehicle, data link and control station to insure that these elements do not limit the total system capabilities in meeting the requirements of 3.3 and/or 3.2. For example, the Vehicle Requirements must include minimum dynamic requirements in the event of short-term, intermittent data link dropouts, and also assure sufficient control authority to satisfy maneuvering response requirements. The Control Station section deals primarily with display information and controller requirements which enable the operator to perform within the total system requirements of 3.3 and/or 3.2.

Finally, the literature search revealed that there is little or no RPV flying qualities data available to permit rational statements as to representative values for the requirements. The few values which are given are intuitive or at best reflect piloted aircraft experience. As more data become available from the follow-on RPV flying qualities programs, further validation and separation of requirements will be achievable.

SECTION II

STATEMENT AND DISCUSSION OF REQUIREMENTS

1. SCOPE AND CLASSIFICATIONS

GENERAL DISCUSSION

Section 1.0 for this specification defines a general framework which permits tailoring each requirement according to:

1. The kind of vehicle (Class).
2. The job to be performed (Flight Phase).
3. How the job is performed (Automatic, Manual Control).
4. How well or easily the job must be performed (Level of Flying Qualities).

The general RPV classification structure for the RPV requirements is somewhat similar to the conventional airplane specification MIL-F-8785B (Reference 2) and the V/STOL specification MIL-F-83300 (Reference 3). Specifically, the RPV classification framework involves the following:

1. Four Vehicle Classes:	The kind of RPV, grouped principally by maneuvering capability and size.
2. Four Flight Phases:	Based on maneuvering, tracking, and flight path control requirements.
3. Two Control Mechanizations:	Automatic (autonavigation, sensor following, or autopilot). Manual (man-in-the-loop)
4. Flying Quality Levels:	How well or easily the vehicle must be flown to do the job. Three flying quality levels are used for <u>each</u> of the two control mechanizations.

Table 1 illustrates how this framework can be used to state different values for a given flying qualities parameter depending on class, flight phase, control mode and desired level of performance. It is unlikely that such a complete or fine breakdown will ever be required. In some cases one set of values will be adequate. The intent, however, is to establish a framework which would be applicable to all conditions.

TABLE 1. FRAMEWORK FOR FLYING QUALITIES REQUIREMENTS

VEHICLE CLASS	FLIGHT PHASE	AUTOMATIC LEVELS			MANUAL LEVELS		
		1A	2A	3A	1M	2M	3M
I	A B C D	● Accomplish Flight Phase ● Normal Operation	● Degraded Flight Phase ● Degrading Failures	● Recover-able ● Minimum Backup Mode Req.	● Accomplish Flight Phase ● Normal Remote Operation *(1 → 3.5)	● Degraded Flight Phase ● Increased Operator Workload *(3.5 → 6.5)	● Recover able ● Minimum Manual Req. *(6.5 → 9+)
II	A B C D						
III	A B C D						
IV	A B C D						

*Cooper-Harper Scale (Reference Figure 6)

The word 'vehicle' is used throughout this document to provide a direct distinction from terminology used in the manned aircraft specifications (i.e., MIL-F-8785, MIL-F-83300). The following definitions are proposed to clarify RPV characteristics:

RPV - An unmanned air vehicle which has the capability of being controlled by a remote operator during some flight phase of an operational mission.

RPV Flying Qualities - Those characteristics of the total RPV that govern the ease and precision with which the remote operator, or the performance with which the automatic flight control system can accomplish the assigned flight phase task.

Total RPV System - A total system entity which includes the basic and augmented vehicle with its stability and control characteristics; automatic and/or manual flight control subsystems; command, control and communication data link subsystems; and operators consoles, displays, and controls required for RPV operation.

1.1 - 1.2 SCOPE AND APPLICATION

REQUIREMENTS

1.1 Scope. This specification contains the requirements for the flying qualities of conventional U.S. military remotely piloted vehicles (RPV's).

1.2 Application. The requirements of this specification shall be applied to assure that no limitations on safe recovery or on the capability to perform intended missions will result from deficiencies in flying qualities. The flying qualities proposed or contracted for shall be in accordance with the provisions of this specification unless specific deviations are authorized by the procuring activity. Additional or alternate special requirements may be specified by the procuring activity. For example, if the form of a requirement should not fit a particular vehicle configuration or control mechanization, the procuring activity may at its discretion agree to modified requirements that will maintain an equivalent degree of acceptability.

DISCUSSION

The word "conventional" in 1.1 implies the more conventional, airplane-type RPV vehicle as opposed to V/STOL configurations. The initial intent was to include both the conventional fixed wing and V/STOL configurations within the framework. The flying qualities specifications for manned conventional and V/STOL aircraft (MIL-F-8785B and MIL-F-83300) indicate a high level of parallelism and similarity. However, there are significant differences in flight parameter priorities, sensitivities, operating ranges, terminology, and methods of control, which would require additional identification within the outline of the requirements. Since the framework for the RPV criteria is already significantly expanded (i.e., inclusion of both automatic and manual control), it was concluded that presenting additional requirements (or variations) for all vehicles would, in the final form, lead to a cumbersome specification that would promote confusion. Thus, the main effort of this study was directed at developing a RPV flying qualities criteria framework for the more conventional airplane-type of RPV vehicle. This is not to say that many of these requirements would not be applicable to V/STOL RPV's in specific instances. However, it is believed that V/STOL criteria can best be handled as an addendum once the basic criteria have been established.

The statement in 1.2, "Additional or alternate special requirements may be specified by the procuring activity" is of particular importance. It is impossible to account for all peculiarities that may arise when considering all possible combinations of missions, methods of control, vehicle configurations, etc. This has been true for aircraft and will continue to be true for RPV's. There are presently insufficient RPV data, and some requirements refer to specific system requirements which would have to be revised when alternate approaches are used. The procuring activity is expected to tailor this general specification for each application to the extent feasible.

1.3 RPV CLASSIFICATIONS

REQUIREMENT

1.3 RPV Classifications. For the purpose of this specification, the RPV shall be placed in one of the following classes.

Class I — Small, light mini RPV's

- Small surveillance, reconnaissance RPV's
- Small target RPV's
- Small demonstration models
- Small electronic warfare RPV's
- Harassment RPV's

Class II — Low-maneuverability RPV's

- High altitude, long endurance (HALE) vehicles
- Surveillance/reconnaissance - high altitude (e.g., Compass Cope)
- Electronic warfare (early warning/electronic countermeasures)
- Relay command/control/communications

Class III — Medium-maneuverability RPV's

- Surveillance, reconnaissance - low altitude
- Low-level terrain following/avoidance missions
- Weapon delivery
- Electronic warfare (Early warning/electronic countermeasures)
- Target RPV
- Modified full-scale MIL-F-8785B Class IV Vehicles

Class IV — Highly maneuverable RPV

- Air-to-air combat target
- Interceptor

The procuring activity will assign a vehicle to one of these Classes, and the requirements for that Class shall apply. When no Class is specified in a requirement, the requirement shall apply to all Classes. When operational missions so dictate, a vehicle of one Class may be required by the procuring activity to meet selected requirements ordinarily specified for a vehicle of another Class.

DISCUSSION

Several RPV vehicle class considerations were investigated:

1. Weight (size) versus maneuverability (g's)
2. Weight (size) versus mission
3. Maneuverability levels (g's)-mission oriented

The weight and maneuverability classes generally apply for piloted aircraft since both relate closely to the type of aircraft and mission to be performed. For example, bombers and heavy transports are large, heavy aircraft with low to medium maneuverability. However, the first two methods of classification do not appear to be desirable here, since RPV's of the same weight class can involve low to high maneuverability ranges and can encompass most or all operational missions.

For the weight/mission class one might envision a classification matrix like the following:

W / M	Small (Mini)	Med (ARPV)	Large
Recce			
Strike			
EW			
Others			

This format results in too many classifications and duplications. Questions are also raised as to what to do with odd or new missions, and this matrix appears to ignore (at lease in a direct sense) one of the more important flying quality characteristics: maneuverability. To illustrate the problem with this classification scheme RPV weight vs. mission characteristics are shown in Figure 3. (The major source was the March 15, 1976 issue of Aviation Week and Space Technology). As already stated there is little correlation between weight and mission.

The approach which appears to provide the best class organization is based on maneuverability. The four selected classes along with present distinct RPV trends are shown in Figure 4. Actual available maneuvering data are limited; however, some values are shown in Figure 5. The small, light mini RPV was defined as a separate category since it is a brand all of its own, ranging from simple radio-controlled vehicles to highly sophisticated systems. The divisions are not intended to indicate exact boundaries, but to outline vehicle types which could require different flying qualities.

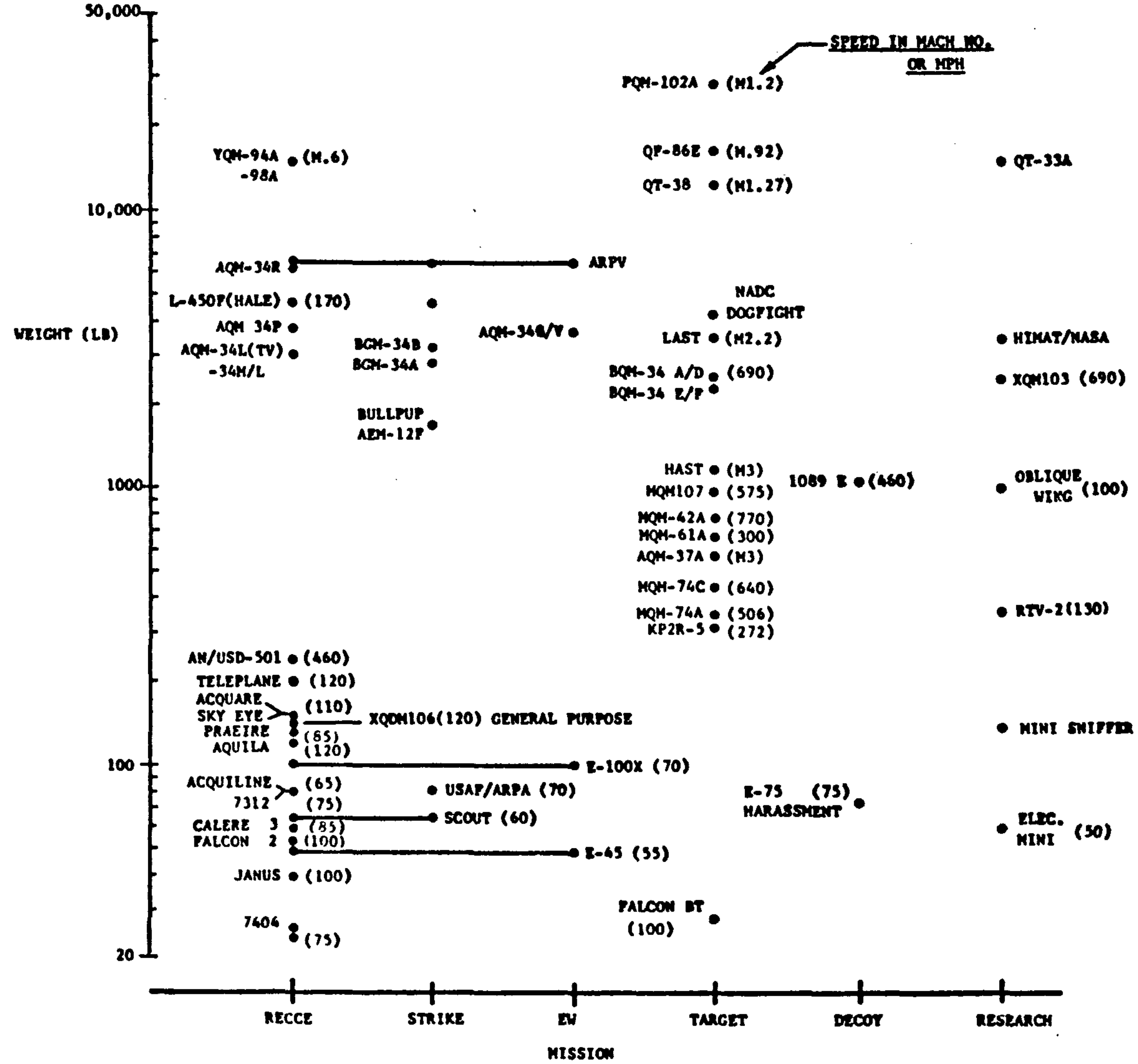


Figure 3. RPV Vehicle Class Considerations - Weight Vs. Mission

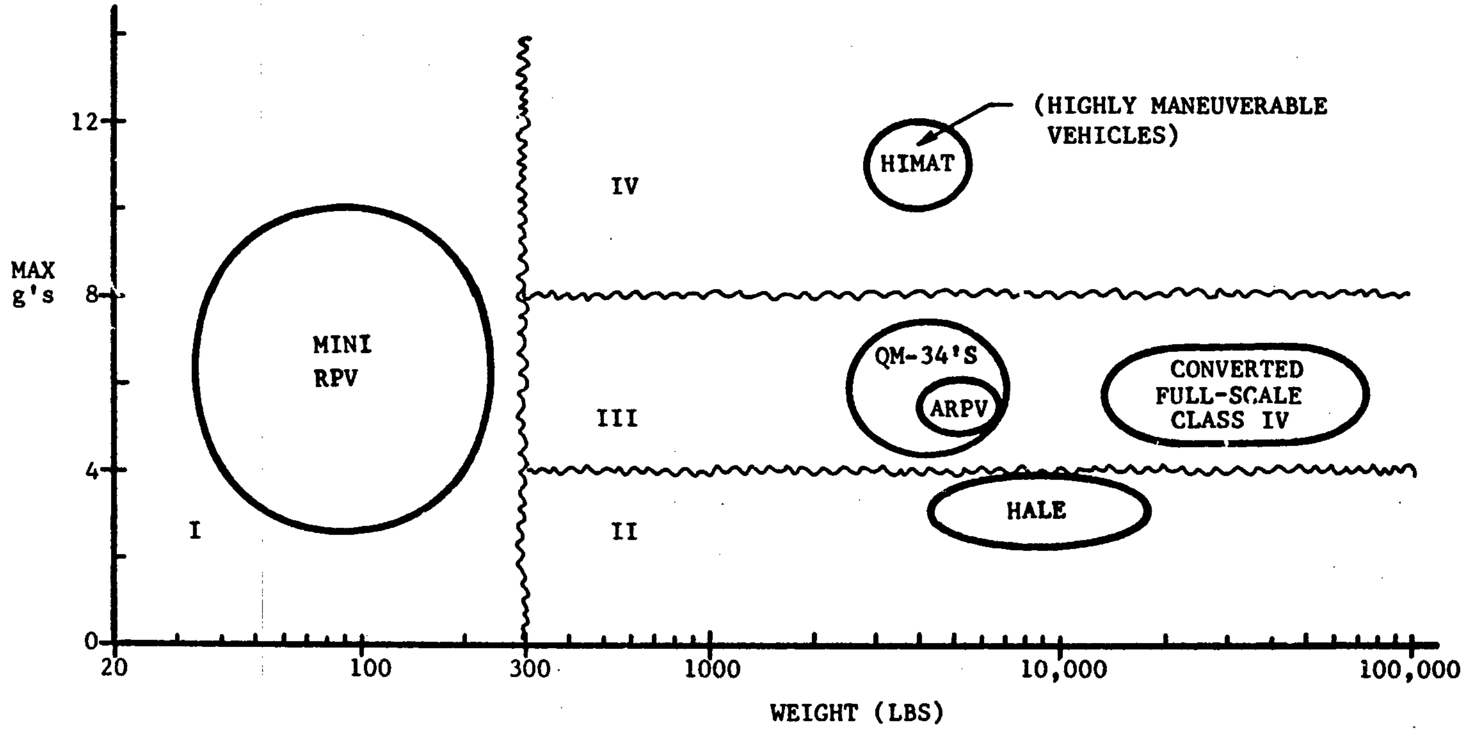


Figure 4. RPV Vehicle Classes

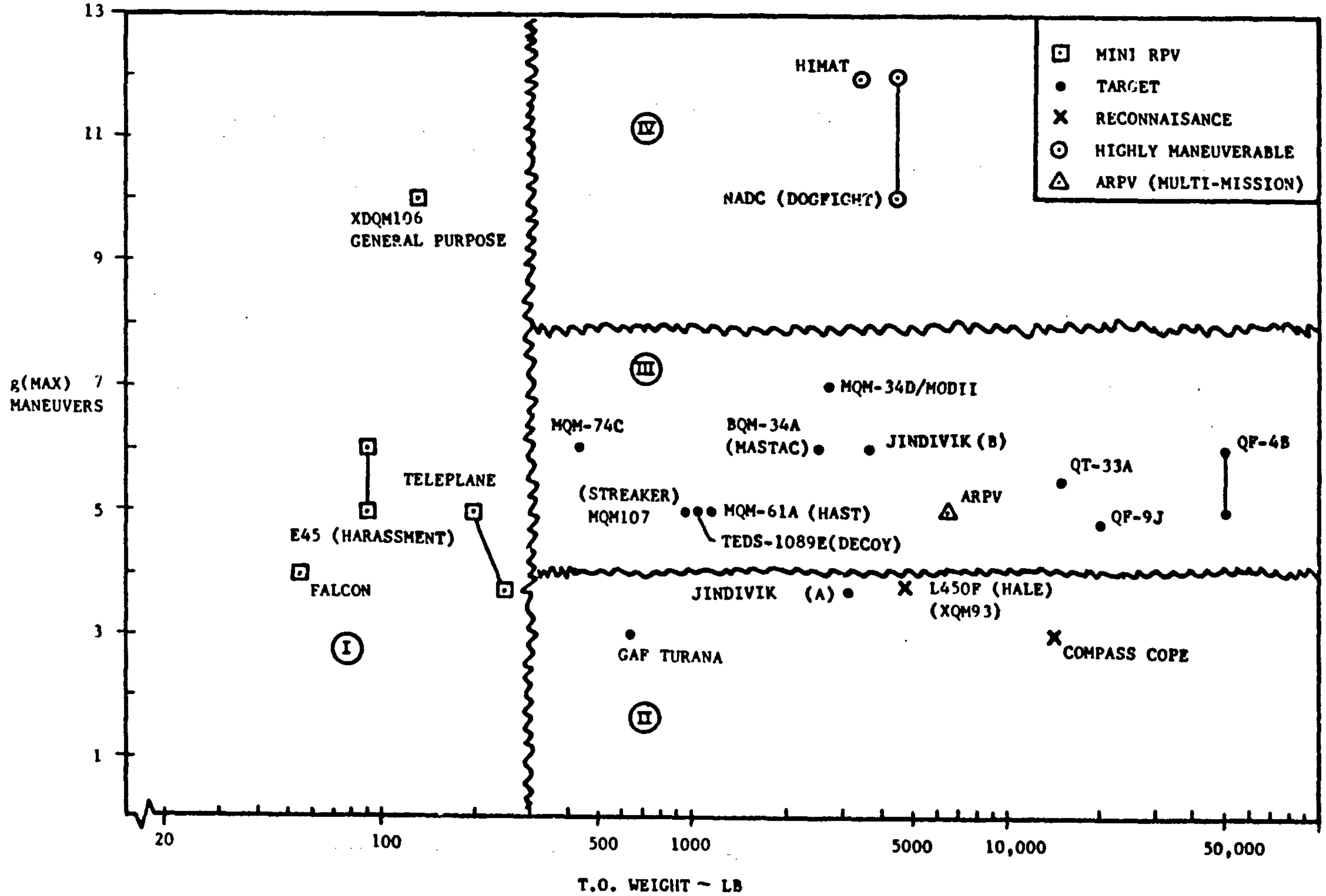


Figure 5. Comparison of RPV Maneuvering Classifications with Data

1.4 FLIGHT PHASE CATEGORIES

REQUIREMENT

1.4 Flight Phase Categories. The flight phases have been combined into four categories which are referred to in the requirement statements. These flight phases shall be considered in the context of total missions so that there will be no gap between successive flight phases, and so that transition will be smooth. When no flight phase or category is stated in a requirement, that requirement shall apply to all four categories. In certain cases, requirements are directed at specific flight phases identified in the requirement. Flight phases of most military RPV missions include:

Category A Flight phases requiring rapid maneuvering, precision tracking, and/or precise flight path control.

(a) Reconnaissance (RC)
(b) Antisubmarine search (AS)
(c) Target acquisition (TA)
(d) Weapon delivery (WD)
(e) Surface attack (SA)
(f) Air-to-air combat (CO)
(g) Terrain following/ avoidance (TF)
(h) Formation Flying (FF)
(i) In-flight refueling (RR)

Category B Flight phases requiring gradual maneuvers without precision tracking, although accurate flight path control may be required.

(a) Climb (C)
(b) Cruise (CR)
(c) Station keeping (loiter) (LO)
(d) Descent (D)
(e) Emergency descent (ED)
(f) Emergency Climb (EC)
(g) Emergency deceleration (DE)
(h) Aerial Delivery (AD)

Category C Launch/recovery flight phases that require rapid maneuvering, precision tracking or precise flignt-path control. Included in this category are:

(a) Arresting gear landings (AG)
(b) Wave-off/go-around (WO)
(c) Midair probe-drogue capture (PDC)
(d) Net capture (NC)
(e) Conventional take-off (TO)
(f) Conventional landing (L)

Category D Launch/recovery flight phases that are normally accomplished using gradual maneuvers and without

precision tracking, although accurate flight-path control may be required. Included in this category are:

(a) Catapult take off (CT)
(b) Approach (PA)
(c) Midair parachute recovery (MAR)
(d) Parachute descent (controlled)
(e) Approach to recovery envelope

When necessary, recategorization or addition of flight phases or delineation of requirements for special situations will be defined by the procuring activity.

DISCUSSION

Four Flight Phase Categories are proposed for RPV's. Basically, these categories provide for precise and non-precise flying up-and-away, and for launch/recovery.

This is one more category than presently defined for piloted aircraft. The added Flight Phase Category comes from dividing the RPV Launch/Recovery into precise and non-precise flight phases. These two categories relate to the Category C-Terminal Flight Phases for piloted aircraft. Of the multitude of possible methods for RPV launch and recovery, some require precise flight path control and tracking (such as an arresting gear or net capture) while others may not (e.g., parachute descent).

The expressions Terminal and Non-Terminal used for manned aircraft have also been dropped because of conflict with existing RPV terminology. RPV flight phases are generally referred to as launch, enroute, terminal (mission phase), and recovery. In general, the Category A-Flight Phases relate to the RPV terminal mission phases and Category B to the RPV enroute phase. There are a few obvious exceptions such as "Terrain Following", which is listed in Category A but is a definite enroute flight phase profile.

Because of the similarity in definitions for Categories B and D, some recommendations suggested combining Categories B and D into one Flight Phase Category. This may be possible; however, Categories B and D also represent flight phases which can involve significant differences in both vehicle configuration (e.g., flaps, gear down, etc.) and flight envelope operation. It is felt at this time that retaining these two categories provides a more consistent framework for tailoring requirements. Further, not all flight phases will apply to a given vehicle. Those that are appropriate to the operational mission and emergencies will be selected for each design.

1.5 LEVEL OF RPV FLYING QUALITIES

REQUIREMENTS

1.5 Level of RPV Flying Qualities. Where possible, the requirements of Section 3 have been stated in terms of values for the RPV flying qualities parameter being specified. Each value is a minimum condition to meet one of the levels of acceptability related to the ability to complete the operational missions for which the vehicle is designed. The three corresponding levels for automatic control and manual control are:

Automatic Control:

Level 1A. (Normal system operation) RPV flying qualities are clearly adequate to accomplish mission flight phase.

Level 2A. (Degraded mission) RPV flying qualities remain adequate to perform mission flight phase with moderate degradation of mission effectiveness.

Level 3A. (Recoverability) Degraded RPV flying qualities remain adequate to recover vehicle. Category A Flight Phases can be terminated successfully; Categories B and C or D Flight Phases can be completed sufficiently to recover vehicle.

Manual Control:

Level 1M. (Normal remote control operation) Operator remote control is clearly adequate to accomplish mission flight phase.

Level 2M. (Degraded mission) RPV can be adequately remotely controlled to perform mission flight phase with a moderate increase in operator work load, a degradation in mission effectiveness, or both.

Level 3M. (Recoverability) Degraded RPV remote control remains adequate to recover vehicle. Workload permits Category A Flight Phases to be terminated successfully; Categories B and C or D Flight Phases can be completed sufficiently to recover vehicle.

DISCUSSION

The phase "where possible" is used for the same reason as in the manned aircraft specifications. The literature search revealed that there is little or no RPV flying qualities data available to permit rational statements as to representative values for the requirements. The few values which are given

are either entirely intuitive or reflect piloted aircraft experience. As more data become available from the follow-on RPV flying qualities programs, further validation and separation of requirements into Levels should be achievable.

Three Levels have been defined for both the automatic and manual flight control. The intent of the corresponding Levels (e.g., 1A and 1M) is the same for both methods of control, except that for automatic, difficulty of control is not a factor. However, it is expected that, in some cases, different values may be required for the two modes at the same Level. It is realistic to assume that the requirements on some vehicle flying quality parameters would be different, for manual and automatic operation. For example, if the remote operator is required to fly the vehicle manually he may require slower control response characteristics than the acceptable response for automatic control, which may be faster depending on control power, structural limitations, and stability characteristics.

Basically the three Levels reflect degradation of flying qualities associated with Vehicle Failure States. Level 2 applies to degradation, or failure of noncritical portions of the flight control system, or use of backup (reversion) modes having reduced capability. Level 3 is the minimum acceptable level, defining requirements for return and safe recovery of the vehicle following a failure at the most adverse point in the mission. Flight must continue through any subsequent flight phases until recovery. Level 3 does not apply to one-way expendable RPV's. Such vehicles involve only Levels 1 and 2, except for vehicle/mission reliability specified by the procuring activity under Vehicle Failure States (3.1.9.2).

The following comments on Level usage, and the pilot rating scale for manual control are the same as those in MIL-F-8785B (Reference 2).

To determine the degradation in flying qualities parameters for a given vehicle failure state the following definitions are provided:

a. Level 1 is better than or equal to the Level 1 boundary, or number given in Section 3.

b. Level 2 is worse than Level 1, but no worse than the Level 2 boundary, or number given in Section 3.

c. Level 3 is worse than Level 2, but no worse than the Level 3 boundary, or number given in Section 3.

When a given boundary, or number, is identified as Level 1 and Level 2, this means that the flying qualities outside the boundary conditions shown, or worse than the number given, are at best Level 3 flying qualities.

The flying quality Levels for manual control are to be directly associated with the pilot rating scale developed by Cooper and Harper and shown in Figure 6. The operator ratings are influenced by how hard he has to work to do the job. The Levels; in turn, identify the satisfactory acceptable and minimum-recoverable values of the flying qualities parameter which the remote operator feels he needs to do the job. The associations among Levels, for past and present rating scales, are (Reference 2):

Level	Original Cooper Scale	Standard CAL Scale	Interim Revision-Cooper-Harper Scale (Ref. 5)	Final Revision-Cooper-Harper Scale (Figure 6)
1	1-3.5	1-3.5	1-3.5	1-3.5
2	2.5-5.5	3.5-6.5	3.5-6.5	3.5-6.5
3	5.5-7	6.5-9+	6.5-9+	6.5-9+

The application of the requirements and their Levels is discussed in more detail in Section 3.1.9.

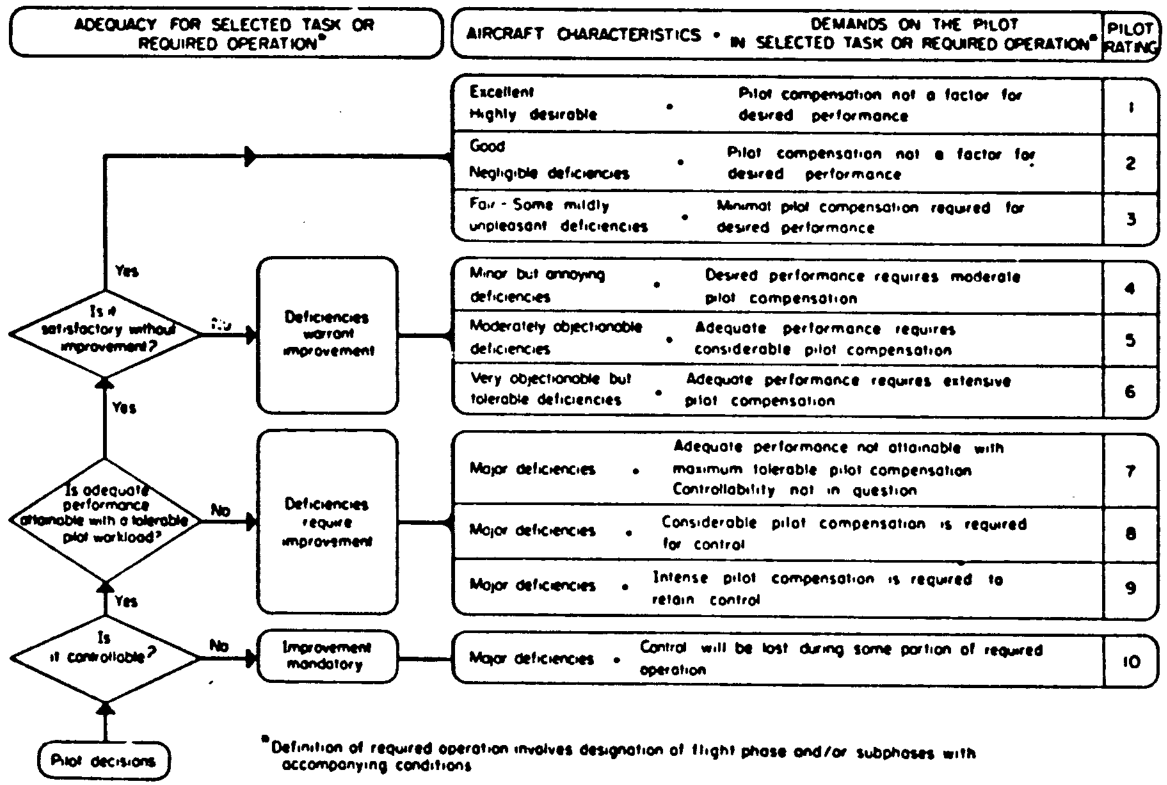


Figure 6. Revised Rating Scale (Reference 2)

1.6 FLIGHT CONTROL MECHANIZATIONS

REQUIREMENTS

1.6 Flight Control Mechanizations

1.6.1 Automatic Control - Automatic flight control system includes control loop components which generate and transmit automatic control commands which provide operator assistance for automatic or semi-automatic flight path control functions, guidance control functions, or automatic control of airframe response to disturbances. This classification includes automatic pilots, automatic navigation/guidance, automatic operator assist modes such as altitude and attitude hold, and automatic flight control functions which may periodically use discrete manual update commands or manually-controlled sensor outputs such as an automatic seeker following mode.

1.6.2 Manual Control - Manual flight control system includes the control loop components which transmit operator-generated flight control commands, and/or generate and convey commands which augment operator-generated commands to accomplish vehicle flight control functions. This classification includes longitudinal, lateral-directional, lift, drag, variable-geometry control, and associated stability and control systems activated during manual control.

DISCUSSION

The requirements of this specification cover both manual and automatic flight control modes and any integrated combinations of manual and automatic operation. The latter may require an additional classification such as semi-automatic; however, the present approach is to classify all control modes as either automatic or manual. The definitions stated above essentially reflect the MIL-F-9490D definitions for automatic and manual flight control systems.

Control mechanizations which are included under automatic control are automatic navigation with periodic manual discrete position updates, and automatic seeker following wherein the operator controls the sensor rather than the vehicle. The rationale is that the principal method of vehicle flight control is performed automatically while the manual interface provides occasional outer-loop command inputs to a closed automatic flight control loop. Preprogrammed, automatically-controlled maneuvers which may be selected and initiated by manual switching are also included under automatic control.

Stability and command augmentation characteristics, relied upon during continuous manual flight control of the vehicle, are to be included when satisfying the manual control requirements of 3.3.2.

2.0 APPLICABLE DOCUMENTS

DISCUSSION

This section was not treated directly in this study. It is dangerous arbitrarily to include documents cited in piloted aircraft specifications because of the more stringent requirements applied to man-rated systems (e.g., reliability). It is highly probable that a number of these documents can be cited for RPV application with noted deletions of sections which do not apply. It is recommended that this subject be treated in Phase IV of the program after the requirements have been more clearly established.

The documents that have been referenced to date in the criteria of this report and are intended to form a part of this specification to the extent specified herein are:

MIL-W-24514D	Weight and Balance Control Data
MIL-STD-756	Reliability Prediction
MIL-STD-1472A	Human Design Design Criteria for Military Systems.
Human Engineering Guide to Equipment Design, 1972	Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402

3. REQUIREMENTS

3.1 GENERAL REQUIREMENTS

GENERAL DISCUSSION

The requirements, organization, and discussions of Section 3.1 closely parallel those of the conventional airplane specification MIL-F-8785B and the piloted V/STOL aircraft specification MIL-F-83300.

In general, Section 3.1 identifies the conditions under which the requirements of this specification apply. These conditions are specified in terms of operational mission requirements for which the vehicle is to be designed; vehicle states (weight, center-of-gravity position, external stores, flight phase configuration and control mode status); and vehicle flight envelopes which specify various conditions of speed, altitude, and load factor.

These requirements outline a relatively detailed procedure for establishing conditions for which the RPV requirements are to apply. Obviously, not all RPV systems will be subjected to such detail (e.g. simple mini RPV's). The procuring activity should establish the level of detail to be considered. However, it is felt that the detail of Section 3.1 is justified for the more complex RPV systems. The intent is to insure a thorough evaluation of all flight conditions for the purpose of identifying the critical design conditions.

3.1.1 MISSION REQUIREMENTS

REQUIREMENTS

3.1.1 Mission Requirements

3.1.1.1 Operational Missions. The procuring activity will specify the operational missions which the contractor is to consider when designing the vehicle to meet the flying qualities requirements of this specification. These missions will include the entire spectrum of intended operational usage.

3.1.1.2 Mission Performance. Except as superseded by specific performance requirements imposed by the procuring activity, the mission performance requirements of Section 3.2 and the related system performance requirements of Section 3.3 shall be used.

DISCUSSION

The mission requirements have been divided into two categories:

- Operational mission requirements which are used to define the overall vehicle design, configuration, loading and operational flight envelopes, and

- Mission performance requirements which establish how well the total system must perform to accomplish the flight phase tasks of the mission successfully. These requirements refer to functional performance accuracies such as navigation position errors, touchdown dispersion, tracking accuracies, flight control accuracies, etc.

A general discussion of the two categories follows.

Operational Missions

In the broadest sense, "operational missions" is applied in terms of the vehicle mission category, such as relay, target, strike, reconnaissance, electronic warfare, etc.; or in terms of the mission function, such as air-to-ground guided weapon delivery, air-to-air combat target. In 3.i.1.1 the object is to define for the designer the function of the vehicle to be designed.

The procuring activity should examine ranges of useful load, flight time, combat speed and altitude, etc. to define the entire spectrum of intended operational use. "Operational missions" are intended to include training missions. Mission profiles which are to be used for performance guarantees should also be defined and included.

The intended use of the RPV vehicle system must be known before the required configurations, loadings, and the operational flight envelopes can be defined,

and the design of the vehicle, to meet the requirements of this specification, can be undertaken. Should the using command decide to use the air vehicle system for an operational mission other than those for which it was designed, the responsibility must be assumed by the using command since the designer can only be held responsible for the requirements specified in the contract covering procurement of the vehicle. If additional missions are foreseen at the time the detail specification is prepared, it is the responsibility of the procuring activity to define the operational requirements to include these missions. Considering the history of RPV adaptation and modification, this consideration applies even more here than to manned aircraft.

Mission Performance

The intent of Section 3.2 is to identify performance characteristics which the procuring activity should consider in defining the mission performance requirements, and to provide a focal point within this specification that identifies and summarizes the overall mission performance which the contractor is to provide. Within the framework of 3.2, the procuring activity should clearly identify which performance and operational requirements of this and other system and vehicle specifications are to be used. The reason for this is that some of the system requirements of 3.3 are stated in terms of performance; in some cases these can be interpreted as mission performance requirements. This is particularly true for automatic guidance functions. Thus, it must be made clear in 3.2 whether the requirement in this specification is to be met or an alternate requirement is to be satisfied. Where any item of performance is not otherwise specified, the applicable performance requirements of this specification will be used.

3.1.2 - 3.1.4 LOADINGS, MOMENTS OF INERTIA, EXTERNAL STORES

REQUIREMENTS

3.1.2 Loadings. The contractor shall define the envelope of center-of-gravity and corresponding weights that will exist for each Flight Phase. These envelopes shall include the most forward and aft center-of-gravity positions as defined in MIL-W-25140. In addition, the contractor shall determine the maximum center-of-gravity excursions attainable through failures in systems or components, such as fuel sequencing, hung stores, etc., for each Flight Phase to be considered in the Failure States of 3.1.6.2. Within these envelopes, plus a growth margin to be specified by the procuring activity, and for the excursions cited above, this specification shall apply.

3.1.3 Moments of Inertia. The contractor shall define the moments of inertia associated with all loadings of 3.1.2. The requirements of this specification shall apply for all moments of inertia so defined.

3.1.4 External Stores. The requirements of this specification shall apply for all combinations of external stores required by the operational missions. The effects of external stores on the weight, moments of inertia, center-of-gravity position, and aerodynamic characteristics of the vehicle shall be considered for each mission Flight Phase. When the stores contain expendable loads, the requirements of this specification apply throughout the range of store loadings. The external stores and store combinations to be considered for flying qualities design will be specified by the procuring activity. In establishing external store combinations to be investigated, consideration shall be given to asymmetric as well as to symmetric combinations.

DISCUSSION (Essentially same as MIL-F-8785B)

The loading of a vehicle is determined by what is in (internal loading), and attached to (external loading) the vehicle. The parameters that define different characteristics of the loading are weight, center-of-gravity position, and moments and products of inertia. External stores affect all these parameters and also affect aerodynamic coefficients. In addition, load distribution may conceivably affect the aeroelastic deflection of a very flexible vehicle enough to affect flying qualities differently when the distribution changes.

The requirements of this specification apply under all loading conditions associated with the vehicle's operational missions. Since there are an infinite number of possible internal and external loadings, each requirement generally is only examined at the critical loading with respect to the requirement. Only permissible center-of-gravity positions need be considered for vehicle Normal States. Any fuel sequencing and transfer failures or malperformance that result in center-of-gravity locations outside the established limits are to be considered as Vehicle Failure States. The worst possible

cases that are not approved Special Failure States (3.1.6.2.1) must be examined.

Since the requirements apply over the full range of service loadings, effects of fuel slosh and shifting should be taken into account in design. Balance, controllability, and airframe and structural dynamic characteristics may be affected. For example, take-off acceleration has been known to shift the c.g. embarassingly far aft for airplanes. Attitude may also have an effect. Other factors to consider are fuel sequencing, in-flight refueling, if applicable, and all arrangements of variable, disposable and removable items required for each operational mission.

The procuring activity may elect to specify a growth margin in c.g. travel to allow for uncertainties in weight distribution, stability level and other design factors, and for possible future variations in operational loading and use.

In determining the range of store loadings to be specified in the contract, the procuring activity should consider such factors as stores mixes, possible points of attachment, and asymmetries--initial, after each pass, and the result of failure to release. The contractor may find it necessary to propose limitations on store loading to avoid excessive design penalties.

The designer should attempt to assure that there are no restrictions on store loading, within the range of design stores. However, it is recognized that occassionally this goal will be impracticable on some designs. It may be impossible to avoid exceeding vehicle limits, or excessive design penalties may be incurred. Then, insofar as considerations such as standardized stores permit, it should be made physically impossible to violate necessary store loading restrictions. If this too should not be practicable, the contractor should submit both an analysis of the effects on flying qualities of violating the restrictions and an estimate of the likelihood that the restrictions will be exceeded.

3.1.5 CONFIGURATIONS

REQUIREMENTS

3.1.5 Configurations. The requirements of this specification shall apply for all configurations required or encountered in the applicable Flight Phases of 1.4. A selected configuration is defined by the positions and adjustments of the various selectors and controls available to the operator(s) except for pitch, roll, yaw, throttle and trim controls. Examples are: flap, wing sweep angle, and speed brake setting, landing gear up or down, automatic or manual flight control selections, and stability augumentation selections. The selected configurations to be examined must consist of those required for performance and mission accomplishment. Additional configurations to be investigated may be defined by the procuring activity.

DISCUSSION (Essentially the same as MIL-F-8785B)

The settings of such controls as flaps, speed brakes, and landing gear are related uniquely to each vehicle design. The specification requires that the configurations to be examined shall be those required for performance and mission accomplishment. The position of roll, pitch, yaw controls, trim controls and the thrust magnitude control are not included in the definition of configuration since the positions of these controls are usually specified in the individual requirements, or determined by the specified flight conditions.

Where a distinction is possible, the requirements are stated for Flight Phases, rather than for vehicle configurations, since the flying qualities should be a function of the job to be done rather than of the configuration of the aircraft. However, the designer must define the configuration or configurations which his vehicle will have during each Flight Phase.

3.1.6 STATE OF VEHICLE, NORMAL STATES, FAILURE STATES, SPECIAL FAILURE STATES

REQUIREMENTS

3.1.6 State of the Vehicle. The State of the RPV is defined by the selected configuration together with the functional status of each of the vehicle components or systems, throttle setting, weight, moments of inertia, center-of-gravity position, and external store complement. The trim setting and the positions of the yaw, roll, and pitch controls are not included in the definition of Vehicle State since they are often specified in the requirements.

3.1.6.1 Vehicle Normal States. The contractor shall define and tabulate all pertinent items to describe the Vehicle Normal (no component or system failure) State(s) associated with each of the applicable Flight Phases. This tabulation shall be in the format shown in Table 2.

Certain items, such as weight, moments of inertia, center-of-gravity position, wing sweep, thrust magnitude, or thrust control angle may vary continuously over a range of values during a Flight Phase. The contractor shall replace this continuous variation by a limited number of values of the parameter in question which will be treated as specific states, and which include the most critical values and the extremes encountered during the Flight Phase in question.

3.1.6.2 Vehicle Failure States. The contractor shall define and tabulate all Vehicle Failure States, which consist of Vehicle Normal States modified by one or more malfunctions in vehicle components or systems; for example, a discrepancy between a selected configuration and an actual configuration. Those malfunctions that result in center-of-gravity positions outside the center-of-gravity envelope defined in 3.1.2 shall be included. Each mode of failure shall be considered. Failures occurring in any Flight Phase shall be considered in all subsequent Flight Phases.

3.1.6.2.1 Vehicle Special Failure States. Certain components, systems, or combinations thereof may have extremely remote probability of failure and may, in turn, be very difficult to predict with any degree of accuracy. Special Failure States of this type need not be considered in complying with the requirements of Section 3 if justification for considering the Failure States as Special is submitted by the contractor and approved by the procuring activity.

DISCUSSION (Essentially the same as MIL-F-8785B)

The above introduces vehicle state terminology for use in applying the requirements. The vehicle states identify the selected vehicle configurations together with functional values of vehicle parameters for each applicable flight phase.

TABLE 2. VEHICLE NORMAL STATES

Flight Phase		Weight	C.G.	External Stores	Thrust	Thrust Vector Angle	High Lift Devices	Wing Sweep	Wing Incidence	Landing Gear	Speed Brakes	Bomb Bay or Cargo Doors	Stability Augmentation	Others
Takeoff	TO													
Climb	CL													
Cruise	CP													
Coordinated Turns	CT													
Loiter	LO													
Descent	D													
Emergency Descent	ED													
Emergency Deceleration	DE													
Approach	PA													
Wave-off/ Go-Around	WO													
Landing	L													
Air-to-air Combat	CO													
Ground Attack	GA													
Weapon Delivery/ Launch	WD													
Aerial Delivery	AD													
Aerial Recovery	AR													
Reconnaissance	RC													
Refuel Receiver	RR													
Terrain Following	TF													
Surface Search	SS													
Close Formation Flying	FF													
Catapult Takeoff	CT													

The vehicle normal states refer to normal operation (no component or system failures). The contractor is required to define the vehicle normal states for each required flight phase in the format of Table 2.

A particular design may have other variable features such as air inlets; if the position of any such feature can affect flying qualities independently of the items in Table 2, its position should be tabulated as well. A variable parameter should be presented in discrete steps small enough to allow accurate interpolation in order to find the most critical values or combinations for each requirement. Those critical cases should be identified in the table. As discussed under 3.1.2 - 3.1.4, center-of-gravity positions that can be attained only with prohibited, failed, or malfunctioning fuel sequencing need not be considered for Vehicle Normal States.

There is more to determining Failure States than just considering each component failure in turn. Two other types of effects must be considered. First, failure of one component in a certain mode may itself induce other failures in the system, so failure propagation must be investigated. Second, one event may cause loss of more than one part of the system.

In most cases, a considerable amount of engineering judgement will influence the procuring activity's decision to allow or disallow a proposed vehicle Special Failure State. Probabilities that are extremely remote are exceptionally difficult to predict accurately. Judgments will weigh consequences against feasibility of improvement or alternatives, and against projected ability to keep high standards throughout design, qualification, production, use and maintenance. Generally, Special Failure States should be brought to the attention of those concerned with flight safety. Vehicle Special Failure States, in conjunction with certain requirements that must be met regardless of component or equipment status, can be used to require a level of stability for the basic airframe, limit control to alleviate pitch-up, require an auxiliary power source, force consideration of vulnerability, etc. The procuring activity should state those considerations they wish to impose, as completely as they can, at the outset; but it is evident that many decisions must be made subjectively and many will be influenced by the specific design.

The above discussion reflects applicable comments from MIL-F-8785B. It is felt that the Special Failure States Requirement (3.1.6.2.1) for granting approval is not very specific. In future development of the RPV criteria, consideration may be given to the possibility of specifying a remote failure probability to be used for granting Special Failure States approval [e.g., P(worse than Level 3) $< 10^{-n}$ per flight; where n is to be determined].

3.1.7 - 3.1.8 OPERATIONAL ENVELOPES AND SERVICE ENVELOPES

GENERAL DISCUSSION

The intended purpose of the Operational and Service Flight Envelopes is to accomplish the following:

- To ensure that the more stringent flying quality requirements are applied to those flight conditions essential for mission success (Operational Envelope).

- To ensure that adequate flying qualities exist for the entire operating range of the vehicle and any deterioration of handling qualities will be gradual as flight proceeds from the limits of the Operational Flight Envelope into the Service Flight Envelope. This provides some degree of mission effectiveness for possible unforeseen alternate uses of the vehicles, and it also allows for possible inadvertent flight outside the Operational Flight Envelope.

- To more closely define the design task, in order to avoid performance, cost, and complexity penalties associated with overdesign which attempts to provide excellent flying qualities at all flight conditions.

To start with, the procuring activity must set down the capability it wants for primary and alternate missions, including maneuverability over the speed-altitude range. These are the minimum requirements on the Operational Flight Envelopes.

At this stage the Flight Phases will be known. In response to these and other requirements, the contractor relates Normal States of the RPV design to the Flight Phases. The contractor then:

- Defines the Operational Flight Envelope for each Flight Phase, based on the associated RPV Normal States, and

- Constructs the larger Service Flight Envelope for the RPV Normal State associated with each Flight Phase, beyond which operation is not allowed.

Some Flight Phases of the same category will involve the same or very similar Vehicle Normal States; thus one set of flight envelopes may represent several Flight Phases. However, each envelope must include the flight conditions related to any pertinent performance guarantees. Flight conditions which must be considered are:

o <u>Loadings</u>: Each flight phase will, in general, involve a range of loadings. Generally it will be convenient to represent this

variation by superimposing boundaries for the discrete loading of Table 3. When different external store complements affect the envelope, it may be necessary to construct several sets of envelopes.

- Vehicle Configuration: The vehicle configurations are normally related to the flight phase which the flight envelope represents. The operational boundaries for ranges in configuration variables should be shown for sufficient increments to demonstrate continuity from one flight phase configuration to another, and the extremes.

- Performance: Each flight envelope must include flight conditions related to any performance guarantees.

- Failure States: Separate Flight Envelopes are not normally required for Vehicle Failure States. It is rational to consider most failures throughout the Flight Envelopes associated with Vehicle Normal States. There may be exceptions such as wing sweep failure that necessitates a wing-aft landing, or a flap failure that requires a higher landing speed. In such cases the procuring activity may have to accept some smaller Flight Envelopes for specific Failure States, making sure that these Envelopes are large enough for safe Level 2 or Level 3 operation.

It is apparent that the Flight Envelopes must and can be refined, as the design is further analyzed and defined, by agreement between the contractor and the procuring activity.

The requirements of the specification are to apply at all points within the three-dimensional volume (speed, altitude and normal load factor, and possibly additional performance parameters such as rate of descent, flight path angle or side velocity) of the Flight Envelope, and also within the range of configurations. Hence, in effect, the requirements can apply to a four-dimensional volume (or more if there is more than one independent configuration variable). In picking the conditions within this n- dimensional space at which to determine compliance, consideration should be given to the critical flight conditions and how the vehicle will be flight tested.

Flight test will be conducted to evaluate the vehicle against requirements in known (a priori) Flight Envelopes. Generally, flight tests will cover the Service Flight Envelope, with specific tests on the design limits. The same test procedure usually applies in both Service and Operational envelopes; only the numerical requirements and qualitative Levels differ. If, for example, speed and altitude are within the Operational Flight Envelope but normal load factor is between the Operational and Service Flight Envelope Boundaries, the requirements for the Service Flight Envelope apply. Ideally, the flight test program should also lead to definition of Flight Envelopes depict-

TABLE 3. OPERATIONAL FLIGHT ENVELOPE

FLIGHT PHASE CATEGORY	FLIGHT PHASE	AIRSPEED		ALTITUDE		LOAD FACTOR	
		$V_{o_{min}}$ ($M_{o_{min}}$)	$V_{o_{max}}$ ($M_{o_{max}}$)	$h_{o_{min}}$	$h_{o_{max}}$	$n_{o_{min}}$	$n_{o_{max}}$
A	AIR-TO-AIR COMBAT (CO)	1.4 V_s	V_{MAT}	MSL	Combat Ceiling	-1.0 (n_L)	n_L
	GROUND ATTACK (GA)	1.3 V_s	V_{MRT}	MSL	Medium	-1.0 (n_L)	n_L
	WEAPON DELIVERY/LAUNCH (WD)	V_{range}	V_{MAT}	MSL	Combat Ceiling	.5 (*)	*
	AERIAL RECOVERY (AR)	1.2 V_S	V_{MRT}	MSL	Combat Ceiling	.5 ($-n_L$)	n_L
	RECONNAISSANCE (RC)	1.3 V_S	V_{MAT}	MSL	Combat Ceiling	*	*
	IN-FLIGHT REFUEL (RECEIVER) (RR)	1.2 V_S	V_{MRT}	MSL	Combat Ceiling	.5	2.0
	TERRAIN FOLLOWING (TF)	V_{range}	V_{MAT}	MSL	10,000 ft.	.0 ($-n_L$)	3.5 (n_L)
	ANTISUBMARINE SEARCH (AS)	1.2 V_S	V_{MRT}	MSL	Medium	0	2.0
	CLOSE FORMATION FLYING (FF)	1.4 V_s	V_{MAT}	MSL	Combat Ceiling	($-n_L$)	n_L
B	CLIMB (CL)	.85 $V_{R/C}$	1.3 $V_{R/C}$	MSL	Cruising Ceiling	.5	2.0
	CRUISE (CR)	V_{range}	V_{NRT}	MSL	Cruising Ceiling	.5	2.0
	(COORDINATED TURNS)	(V_{range})	(V_{NRT})	(MSL)	Cruising Ceiling	(*)	(n_L)
	LOITER (LO)	.85 V_{end}	1.3 V_{end}	MSL	Cruising Ceiling	.5	2.0
	IN-FLIGHT REFUEL (TANKER) (RT)	1.4 V_S	V_{MAT}	MSL	Cruising Ceiling	.5	2.0
	DESCENT (D)	1.4 V_S	V_{MAT}	MSL	Cruising Ceiling	.5	2.0
	EMERGENCY DESCENT (ED)	1.4 V_S	V_{max}	MSL	Cruising Ceiling	.5	2.0
	EMERGENCY DECELERATION (DE)	1.4 V_S	V_{max}	MSL	Cruising Ceiling	.5	2.0
	AERIAL DELIVERY (AD)	1.2 V_S	200 kt	MSL	10,000 ft.	0	2.0
C and D	TAKEOFF (TO)	Minimum Normal Takeoff Speed	V_{max}	MSL	10,000 ft.	.5	2.0
	CATAPULT TAKEOFF (CT)	Minimum Catapult End Airspeed	$V_{o_{min}}$ +30 kt	MSL	---	.5	n_L
	APPROACH (PA)	Minimum Normal Approach Speed	V_{max}	MSL	10,000 ft.	.5	2.0
	WAVE-OFF/GO-AROUND (WO)	Minimum Normal Approach Speed	V_{max}	MSL	10,000 ft.	.5	2.0
	LAND (L)	Minimum Normal Landing Speed	V_{max}	MSL	10,000 ft.	.5	2.0

*Appropriate to the operational mission.

ing Level 1 and Level 2 boundaries (paragraph 1.5). These Level boundaries should aid the using commands in tactical employment, even long after the procurement contract has been closed out.

3.1.7 OPERATIONAL FLIGHT ENVELOPES

REQUIREMENT

3.1.7 Operational Flight Envelopes. The Operational Flight Envelopes define the boundaries in terms of speed, altitude, and load factor within which the vehicle must be capable of operating in order to accomplish the missions of 3.1.1.1. Additional envelopes in terms of parameters such as rate of descent, flight-path angle, and side velocity may also be specified. Envelopes for each applicable Flight Phase shall be established with the guidance and approval of the procuring activity. In the absence of specific guidance, the contractor shall use the representative conditions in Table 3.

DISCUSSION (Essentially the same as MIL-F-8785B)

Operational Flight Envelopes are regions in speed-altitude-load factor space (additional parameters such as rate of descent, flight path angle and side velocity may also be specified) where it is necessary for a vehicle, in the configurations and loadings associated with a given Flight Phase, to have very good flying qualities. The Operational Flight Envelopes are intended to permit the design task to be more closely defined. As a result, the cost and complexity of the vehicle and, possibly, the cost and time required for flight testing should be appreciably, but logically, reduced. The required size of the Operational Flight Envelopes for a particular vehicle should, to the extent possible, be given in the detail specification for the vehicle, but some boundaries can only be delineated during design. In defining the speed-altitude-load-factor combinations to be encompassed, the following factors should be considered:

(a) The Operational Flight Envelope for a given Flight Phase should initially be considered to be as large a portion of the associated Service Flight Envelope as possible, to permit the greatest freedom of use of the vehicle by the using command.

(b) If design trade-offs indicate that significant penalties (in terms of performance, cost, system complexity, or realiability) are required to provide Level 1 flying qualities in the large Envelope of (a) above, consideration should be given to restricting the Operational Flight Envelope consistent with the Flight Phase requirement for the operational mission under consideration.

Guidance for establishing Operational Flight Envelopes for various Flight Phases is contained in Table 3 and Figure 7, and is essentially the same as given in MIL-F-8785B. Speed and altitude considerations have not been changed from those of manned aircraft. For RPV's care should be taken to allow sufficient stall margin for approach and landing. This is particularly important when remote manual control is used. The proposed 1.2-1.4 V_s margins are

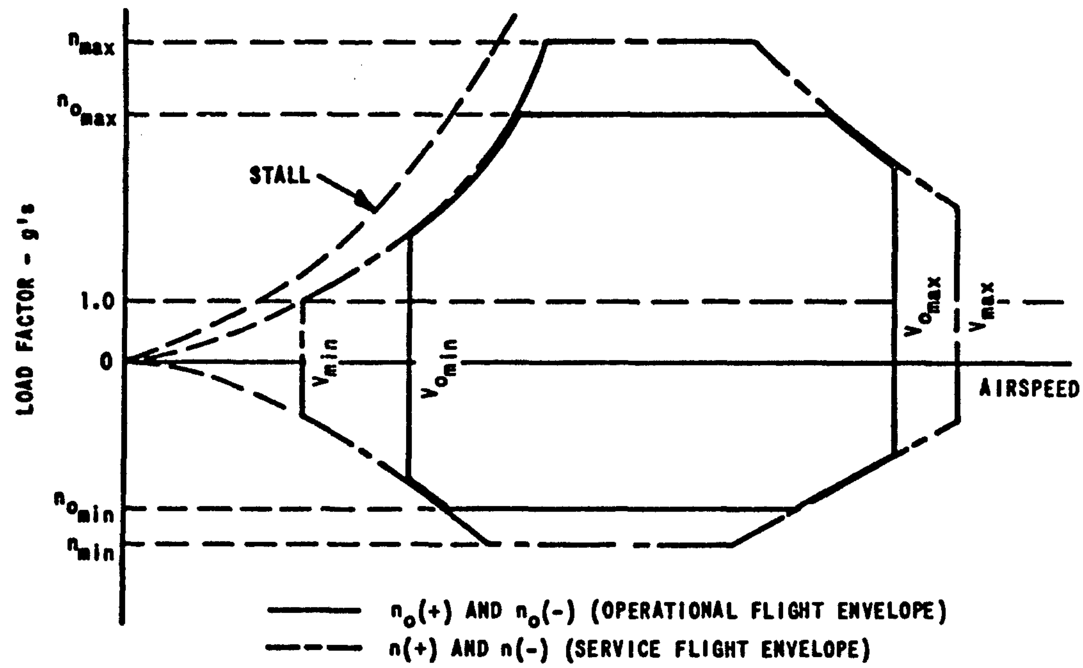


Figure 7. Typical V-n Flight Envelopes for Conventional RPV Configurations (Constant Altitude).

only tentative and represent that used for manned aircraft.

The load factor envelopes as presented in Table 3 are for manned aircraft and undoubtedly reflect pilot restrictions. The parentheses designate proposed changes. For RPV's, the operator is on the ground and is not subjected to the maneuvering load factor. The RPV operational load factor is really only limited by structural considerations, stall, or other stability and control limitations. These limits are determined by the most critical mission flight phase requirements. Many of the critical load factor flight phases are in Category A, which requires rapid maneuvering. This is reflected in Table 3 by expanding the load factor envelope to include the total symmetrical flight limit load factors for a given Vehicle Normal State, based on structural considerations ($\pm n_L$). These proposed changes only represent a 'first pass' at the flight envelope load factors. The intent is to point out the need to remove unnecessary load factor restrictions which are manned aircraft oriented. The RPV flight limit load factor envelopes should be tailored to the flight phase requirements to insure adequate performance capability. Aside from the addition of 'coordinated turns' (Category B) no further changes are proposed at this time.

It is obvious that these tables only serve as a guide for establishing the Operational Flight Envelope. The parameter values stated are approximate. The detail specification issued by procurement should be as specific as possible about speed, altitude and corresponding load-factor requirements. Obviously n_L cannot be attained at "lift-limited" combat ceiling. The procuring activity should assure that the Operational Flight Envelopes encompass the flight conditions at which all mission performance guarantees will be demonstrated.

3.1.8 SERVICE FLIGHT ENVELOPES

REQUIREMENTS

3.1.8 Service Flight Envelopes. For each Vehicle Normal State (but with thrust varying as required), the contractor shall establish, subject to the approval of the procuring activity, Service Flight Envelopes showing combinations of speed, altitude, and load factor derived from aircraft limits as distinguished from mission requirements. Additional envelopes in terms of parameters such as rate of descent, flight-path angle, and side velocity may also be specified. A certain set or range of Vehicle Normal States may be employed in the conduct of a Flight Phase. The Service Flight Envelopes for these States, taken together, shall at least cover the Operational Flight Envelope for the pertinent Flight Phase. The speed, altitude, and load factor boundaries of the Service Flight Envelopes shall be based on considerations discussed in Paragraphs 3.1.8.1 through 3.1.8.5.

3.1.8.1 Maximum Service Speed. The maximum service speed, V_{max}, for each altitude below the service ceiling for the configuration under consideration is the lowest of:

a. The speed which is a safe margin below the value at which intolerable buffet or structural vibration is encountered.

b. The maximum airspeed, in descents, from which recovery can be made without penetrating a safe margin from loss of control, intolerable buffet, or other dangerous behavior, and without exceeding structural limits.

3.1.8.2 Minimum Service Speed. The minimum service speed, V_{min}, for each altitude below the service ceiling for the configuration under consideration is the highest algebraically of:

a. The speed which is a safe margin above the speed at which intolerable buffet or structural vibration is encountered

b. Lowest speed which is a safe margin above the value where pitch, roll, or yaw control available is insufficient to maintain 1-g level flight.

c. 1.1 Vs

d. Vs + 10 knots equivalent airspeed

3.1.8.3 Service Side Velocity. When direct side force control is used, the service side-velocity boundary for the configuration under consideration is defined by the maximum side velocity associated with each speed between V_{max}

and V_{min} (as defined by 3.1.8.1 and 3.1.8.2) from which recovery to straight and level flight can be made without penetrating a safe margin from loss of control or other dangerous behavior.

3.1.8.4 Maximum Service Altitude. The maximum service altitude, h_{max}, for a given speed is the maximum altitude at which a rate of climb of 100 feet per minute can be maintained in unaccelerated flight with MAT (Maximum Augmented Thrust).

3.1.8.5 Service Load Factors. Maximum [and minimum] service load factors, n (+) [n(-)] shall be established as a function of speed for several significant altitudes. The maximum [minimum] service load factor, when trimmed for 1-g flight at a particular speed and altitude, is the lowest [highest] algebraically of:

a. The positive [negative] structural limit load factor

b. A safe margin below [above] the load factor at which intolerable buffet or structural vibration is encountered.

c. The steady load factor at which pitch control is in full vehicle nose-up [nose-down] position.

DISCUSSION

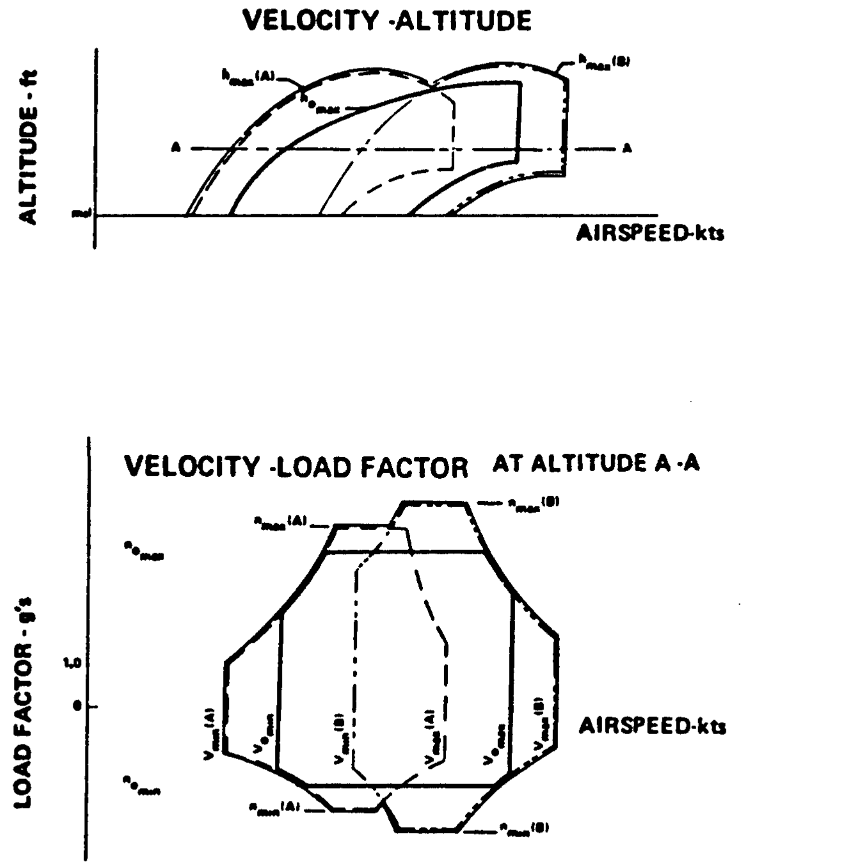
For each vehicle normal state (with thrust varying as required) there is an associated Service Flight Envelope which defines the safe vehicle operating limits for speed, altitude, load factor, and any additional flight condition limits as required. The basic limits for safe vehicle operation are defined by the maximum and minimum service speed, the maximum and minimum service load factors, the maximum service altitude, and the service velocity as given in Sections 3.1.8.1 through 3.1.8.5 The service side velocity applies to vehicles capable of such motion (i.e., direct side force control).

The volume formed by the Service Flight Envelope must encompass the Operational Flight Envelope defined by mission requirements, and denotes the extent of flight conditions that can be encountered without fear of exceeding aircraft limitations (safe vehicle margins should be determined analytically and experimentally). The flying quality requirements for the conditions outside the Operational Flight Envelope are less severe (Section 3.1.9.1), but still stringent enough that the automatic or manual control can accomplish the associated mission flight phase. However, mission effectiveness, or operator workload, or both may suffer somewhat even with no failures.

The basic diagrams are V - h and V-n diagrams which define altitude, speed and load factor boundaries. It is important to repeat that the concept of

flight envelopes as defined in this specification applies to fixed configurations identified as Vehicle Normal States. Several Vehicle Normal States may be involved in performing a specific Flight Phase. In these cases the corresponding Service Flight Envelopes taken together shall at least cover the volume of the Operational Flight envelope corresponding to the Flight Phase (Figure 8). A summary of Navy powered target flight envelopes is presented in Figure 1 of Reference 6. Side velocity from lateral translation capability is indicated on a V-n diagram. In picking the altitudes at which to define load-factor envelopes, or other performance requirements, consideration should be given to critical flight conditions, and to how the vehicle will be flight tested (flight testable conditions).

Mission flight phases requiring a particular performance capability may require construction of additional types of performance flight envelopes. Possible examples are descent, rate of climb requirements which can be shown on a V-γ or V-$\dot{h}$ diagram. A further application of such envelopes is to aid in establishing flight conditions for transition from one flight phase to another when configuration changes are required. For example, the conversion from takeoff to cruise, to the landing configurations. An example of this type of service envelope interpretation can be extrapolated from a V-γ flight path sketch shown in Figure 9. Assume that the two Normal States shown are associated with a landing (flaps down) and cruise flight phase (flaps up). The overlap represents the possible region where transition between the flight phases can take place. A performance envelope of this type which showed lines of constant power, and angle of attack (not shown), would indicate an airspeed transition region in terms of minimum power and attitude transients. Although these types of envelopes reflect steady flight, the minimum change between flight conditions would generally imply minimum transients and would be valuable for scheduling functional configuration changes for the Vehicle Normal States.



——— OPERATIONAL FLIGHT ENVELOPE FOR FLIGHT PHASE
—— - - — SERVICE FLIGHT ENVELOPE FOR AIRCRAFT NORMAL STATE-B
— — — SERVICE FLIGHT ENVELOPE FOR AIRCRAFT NORMAL STATE-A
——— OUTER BOUNDARY OF SERVICE FLIGHT ENVELOPES FOR AIRCRAFT NORMAL STATES REQUIRED TO COVER OPERATIONAL FLIGHT PHASE.

Figure 8. Typical Relationship Between Operational Envelope And Service Flight Envelope For A Given Flight Phase Requiring Two Normal States

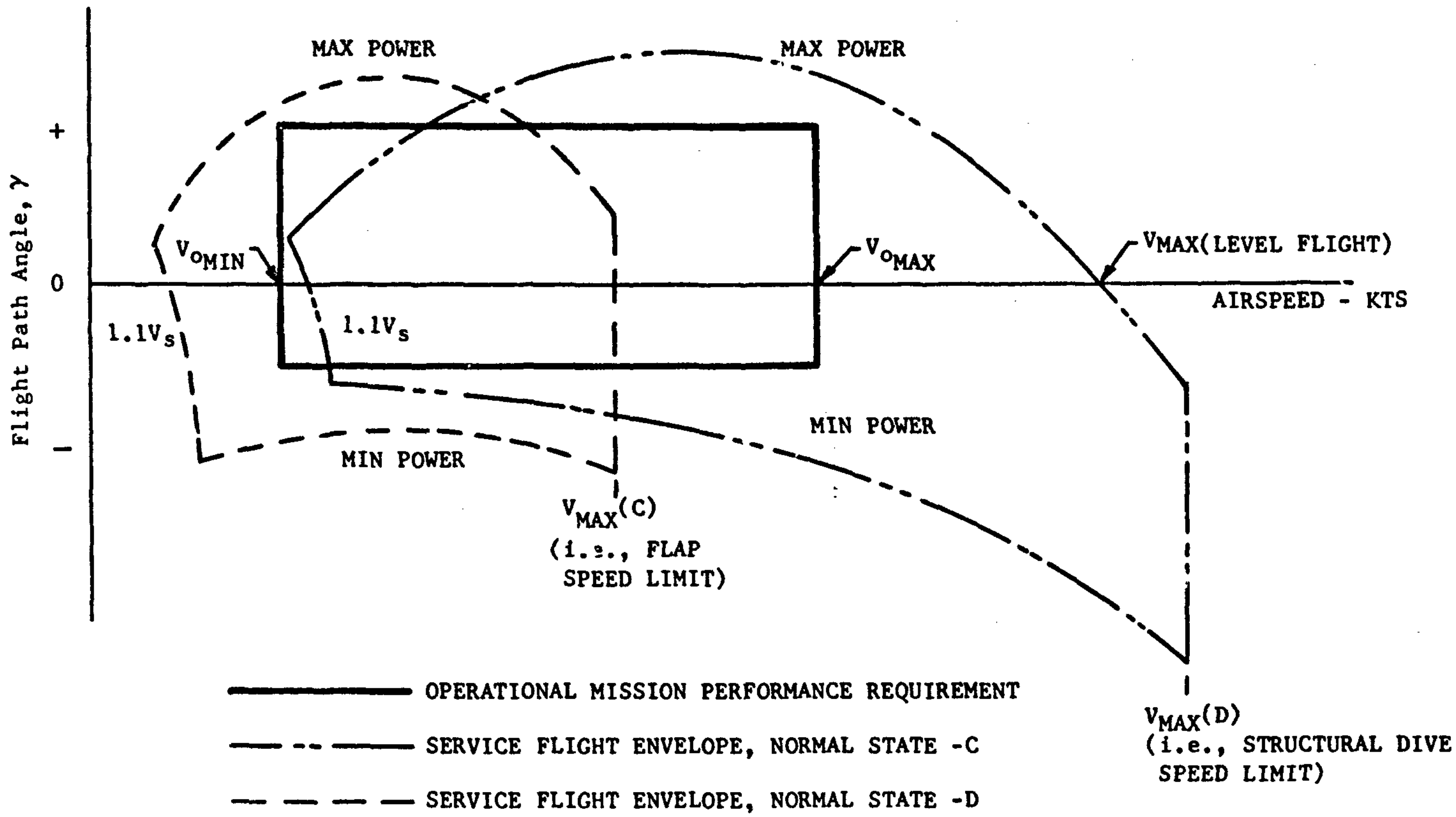


Figure 9. Example Of Performance Or Transition Envelopes

3.1.9 APPLICATION OF LEVELS

REQUIREMENTS

3.1.9 Application of Levels. Levels of flying qualities as indicated in 1.5 are employed in this specification in realization of the possibility that the aircraft may be required to operate under abnormal conditions. Such abnormalities that may occur as a result of either flight outside the Operational Flight Envelope, the failure of aircraft components, or both, are permitted to comply with a degraded level of flying qualities as specified in 3.1.9.1 through 3.1.9.3.2.

3.1.9.1 Requirements for Vehicle Normal States. The minimum required flying qualities for Vehicle Normal States (3.1.6.1) are as shown in Table 4.

TABLE 4 LEVELS FOR VEHICLE NORMAL STATES

Within Operational Flight Envelope	Within Service Flight Envelope
Level 1	Level 2

3.1.9.2 Requirements for Vehicle Failure States. When Vehicle Failure States exist (3.1.6.2), a degradation in flying qualities is permitted only if the probability of encountering a lower Level than specified in 3.1.9.1 is within the reliability requirements of 3.1.9.2.1 thru 3.1.9.2.3. The contractor shall determine, based on the most accurate available data, the probability of occurrence of each Vehicle Failure State per flight and the effect of that Failure State on the flying qualities within the Operational and Service Flight Envelopes. These analyses shall be updated at intervals specified by the procuring activity. These determinations shall be based on MIL-STD-756 except that:(a) all components and systems are assumed to be operating for a time period, per flight, equal to the longest operational mission time to be considered by the contractor in designing the vehicle, and (b) each specific failure is assumed to be present at whichever point in the Flight Envelope being considered is most critical (in the flying qualities sense). From these Failure State probabilities and effects, the contractor shall determine the overall probability, per flight, that one or more flying qualities are degraded below Level 1 in the Operational Flight Envelope, and below Level 2 and below Level 3 in both the Operational and Service Flight Envelopes. These probabilities shall be less than the values defined by requirements of 3.1.9.2.1 thru 3.1.9.2.3. Approved Special Failure states (3.1.6.2.[illegible] [illegible] not to be considered in determining these probabilities.

3.1.9.2.1 Flying Qualities Reliability Within Operational Envelope. A degradation of flying qualities below Level 1 is permitted within the Operational Flight Envelope if the probability of encountering flying quality levels lower than Level 1 are less than 10^{-n} per flight (n to be determined).

3.1.9.2.2 Mission Accomplishment Reliability. The probability of mission failure per flight due to relevant failures in flight control shall not exceed:

$$Q_{M(fc)} \leq (1 - R_M)\, A_M\, (fc)$$

where:

$Q_{M(fc)}$ = Maximum acceptable mission unreliability due to relevant FCS material failures which result in Flying Qualities equal to Level 3 or worse.

R_M = Overall aircraft mission accomplishment reliability specified by procuring activity in Section 3.2.

$A_{M(fc)}$ = Mission accomplishment allocation factor for flight control (chosen by the contractor).

Each mission to which this requirement applies shall be established and defined by the contractor, subject to approval of the procuring activity.

3.1.9.2.3 Vehicle Reliability. The probability of vehicle loss per flight due to relevant failures in the flight control system shall not exceed:

$$Q_{V(fc)} \leq (1 - R_V) \quad A_{V(fcs)}$$

where:

$Q_{V(fc)}$ = Maximum acceptable vehicle loss rate due to relevant FCS failures which result in Flying Qualities worse than Level 3.

$A_{V(fc)}$ = Vehicle reliability allocation factor for flight control (chosen by the contractor).

R_V = Overall vehicle reliability requirement as specified by the procuring activity in Section 3.2.

3.1.9.2.4 Specific Failure State Requirements. When requirements are stated for specific types of failures, they shall be met on the basis that the specific failure has occurred regardless of its probability of occurrence.

3.1.9.3 Exceptions.

3.1.9.3.1 Ground Operation. Some requirements pertaining to takeoff, landing, and taxiing involve operation outside the Operational and Service Flight Envelopes. When requirements are stated for these conditions, the Levels shall be applied as if the conditions were in the Operational Flight Envelope.

3.1.9.3.2 When Levels are not Specified. Within the Operational and Service Flight Envelopes, all requirements that are not identified with specific Levels shall be met under all conditions of component and system failure except approved Vehicle Special Failure States (3.1.6.2.1).

DISCUSSION

The intent of 3.1.9.1 and 3.1.9.2 is to provide:

- o A reasonable probability of good flying qualities where the vehicle is expected to be used (operational envelope).
- o Acceptable flying qualities in reasonably likely, but infrequently expected conditions (service envelope).
- o A reliability base which ensures that the probability of encountering significantly degraded flying qualities because of component of subsystem failure are within specified mission accomplishment and vehicle recovery reliabilities.
- o A process to assure that all ramifications of reliance on the flight control, stability augmentation, etc., receive the proper attention.

A system approach to the requirement specification is used. The following discusses this concept in some detail.

In specifying RPV vehicle failure state requirements one has to first establish what objectives are to be accomplished:

- o Mission accomplishment reliability
- o Vehicle flight reliability - vehicle losses usually referred to as flight safety for manned aircraft
- o Flying qualities reliability

MIL-F-9490D (flight control systems for piloted aircraft) specifies flight control system reliability requirements which must meet both a mission accomplishment and a vehicle flight safety reliability.

MIL-F-8785B (flying qualities for piloted aircraft) reliability requirements place limits on the probability of encountering Level 2 and Level 3 flying qualities during a mission. No direct requirements are placed on mission accomplishment, except that Levels 1 and 2 are intended to allow mission accomplishment with at least some measure of effectiveness, but Level 3 is not so intended.

Since the specifications are for piloted aircraft, both documents impose stringent requirements on vehicle flight safety reliability (probability of aircraft loss). MIL-F-8785B states that in no case shall a failure state (except approved Special Failure States) degrade flying qualities outside of Level 3. MIL-F-9490D requires an extremely remote probability that FCS failures will cause loss of aircraft (e.g., 5×10^{-7} maximum loss rate for large, Class III aircraft).

The philosophy for RPV vehicles is somewhat different. For manned aircraft, pilot safety was first priority; for RPV's this is not the case (a minimal vehicle loss rate may be acceptable particularly if cost effective).

The philosophy behind the requirements of 3.1.9.2 is the combination of the mission accomplishment, vehicle, and flying quality reliabilities into meaningful and related requirements. Table 5 summarizes the relationship; among the three major conditions associated with a mission, the flying quality levels defined in 1.5, and the requirements for the vehicle failure states. The level approach summarized in the table is straightforward in concept. The requirements specified for normal operation (no system failures) provide desirable flying qualities. Equipment failures, however, either in the flight control system or other subsystems, can cause a degradation in flying qualities. Degradation of flying qualities is acceptable if the probability of such degradation is within the reliability conditions stated in 3.1.9.2.1 to 3.1.9.2.3. Basically, these requirements are intended to provide a reliability base for:

a. <u>Flying Qualities in Operational Flight Envelope</u> - Ensure a reasonable probability of good flying qualities (Level 1 - normal operation) in the operational envelope to accomplish the mission and permit degradation in flying qualities only if the probability of encountering a lower level (Level 2 or worse) is less than specified. This requirement is similar in intent to the Requirement for Failure States (3.1.10.2) of MIL-F-8785B except that it deals only with Operational Flight Envelopes; Service Flight Envelopes have not been included. The RPV is a mission-oriented vehicle and is expected to be operated within the operational envelopes. The expected infrequent operation in the service envelope already permits a minimum flying qualities Level of 2.0 (3.1.9.1). Degradation below Level 2.0 which implies the mission cannot be completed is covered by the Mission Accomplishment Requirement.

TABLE 5. RELATIONSHIP OF MISSION/VEHICLE RELIABILITY REQUIREMENTS AND FLYING QUALITY LEVELS

FLIGHT CONDITION	FLYING QUALITY LEVELS	REQUIREMENT		
• Mission can be completed	1. (Normal Operation)			
	2. (Degraded			Allowable probability for Flying Qualities Reliability within Operational Envelope 3.1.9.2.1
• Mission aborted	3. (Recoverable)		Allowable probability given by Mission Accomplishment Reliability Requirement 3.1.9.2.2	
• Vehicle Lost	Worst Than Level 3	Allowable probability given by Vehicle Reliability Requirement 3.1.9.2.3		

b. Mission Accomplishment Reliability - Ensures that the probability of encountering flying qualities levels worse than Level 2 is within specified mission accomplishment reliabilities and applies to both the Operational and Service Flight Envelopes.

c. Vehicle Reliability - Ensures, that the probability of encountering flying qualities levels worse than Level 3 is within the allowable vehicle loss probabilities specified for the RPV system. This requirement also applies to both the Operational and Service Flight Envelopes.

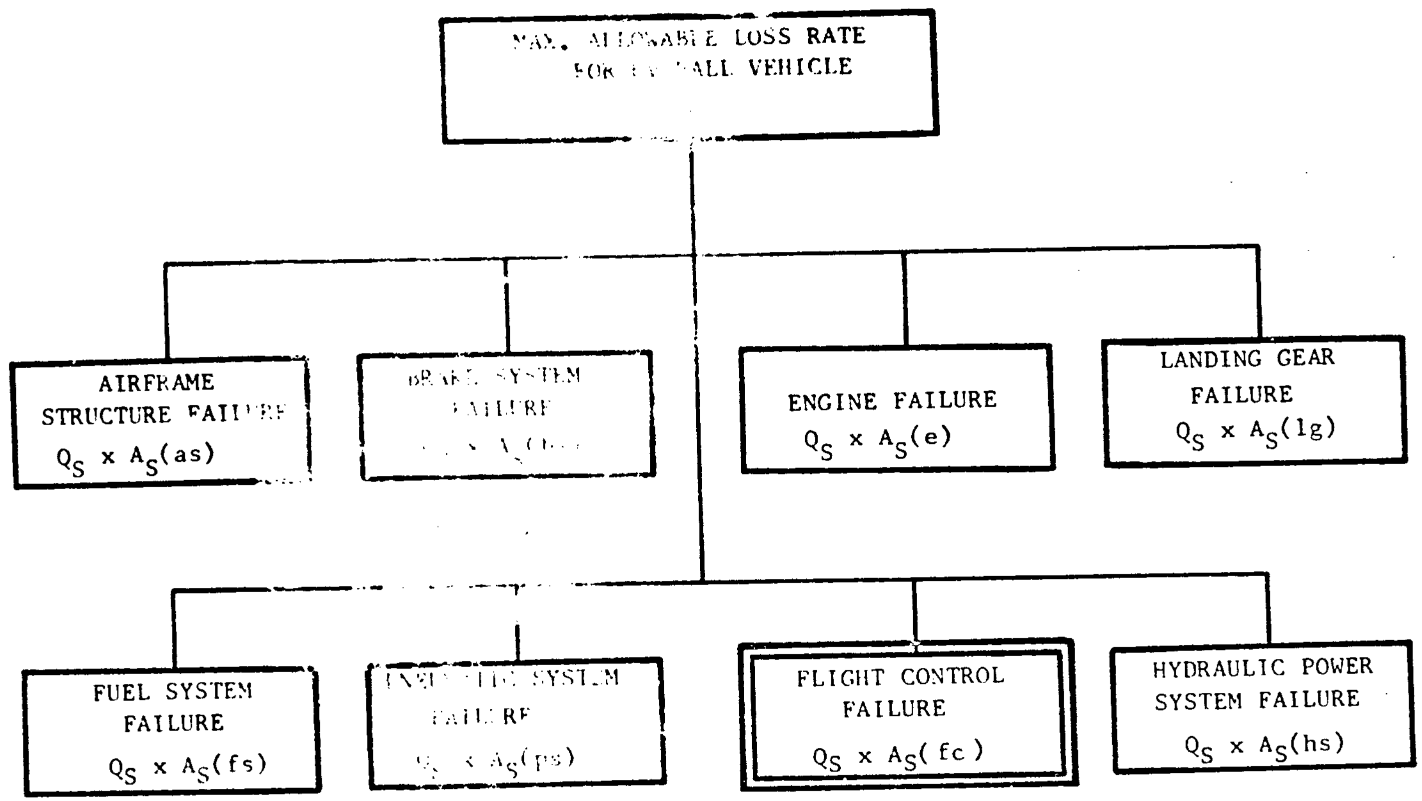
To provide a means for determining compliance, the Mission Accomplishment and Vehicle Reliability requirements are defined in terms of an allocation or budgeting of the overall required reliability. Much more is involved than just flying qualities when mission reliability and vehicle flight reliability are introduced. Such overall reliability requirements involve all vehicle systems, such as engine, airframe, weapon system, fuel systems, etc., and not just those flight control systems and functions normally associated with flying qualities. A typical division is shown in Figure 10.

The budget alloted for the RPV flight control is to include all control loop systems which are involved in generating and transmitting flight control and guidance commands to appropriate force and moment producers on the vehicle. This includes all automatic and/or manual flight control functions that provide vehicle augmentation, flight path control, guidance and aerodynamic configuration control. Among the components included are operator controls, displays, signal computation, signal transmission (i.e., data link), sensors, and actuators dedicated to flight control. Excluded are the airframe, engine, etc., as exemplified in Figure 10. When budgeting system allocations, interdependency of systems must be recognized. Reliability interfaces must be established (e.g., hydraulic, electrical power interfaces with powered flight control systems) and such failures included in the failure analysis of the flight control.

Numerical Values for Probabilities

The actual probabilities allowed will undoubtedly vary from one RPV system to another; these differences require more study and collection of RPV operational statistics. Thus, the reliability requirements define the method for determining compliance but at present do not state specific values. The allowable RPV failures probabilities could conceivably be higher in the interest of simplified design and cost. The degree of back-up systems used to insure either a higher mission completion reliability or a reduction in vehicle losses, or both, will depend on cost effectiveness considerations for the particular RPV system and mission.

Implementation: To determine theoretical compliance with the requirements of 3.1.9.2, the following steps must be performed:



$$Q_S = Q_S \left(A_{S(as)} + A_{S(bs)} + A_{S(e)} + A_{S(lg)} + A_{S(fs)} + A_{S(ps)} + A_{S(fc)} + A_{S(hs)} \cdots \right)$$

Figure 10. Typical Division Of Overall Vehicle Allowable Loss Rate

a. Identify those Vehicle Failure States which have a significant effect on flying qualities (3.1.6.2)

b. Determine the longest flight duration to be encountered during operational missions defined in 3.1.1

c. Determine the probability of encountering various Vehicle Failure States, per flight, based on the above flight duration (3.1.9.2).

d. Determine the degree of flying qualities degradation associated with each Vehicle Failure State in terms of Levels defined in 1.5 and any specific level requirements defined in this specification.

e. Determine the most critical Vehicle Failure States (assuming the failures are present at whichever point in the Flight Envelope being considered is most critical in a flying qualities sense), and compute the total probability of encountering the Levels specified in 3.1.9.2.1 thru 3.1.9.2.3.

f. Compare the computed values with requirements. If the requirements are not met, the designer must consider alternate courses such as:

   1. Improve the airplane flying qualities associated with the more probable Failures States, or

   2. Reduce the probability of encountering the more probable Failure States through equipment redesign, redundancy, etc. (Reference flight control reliability 3.3.4.4.)

Failure [illegible] influence the vehicle operating configuration, and even the mission Fl[illegible] [illegible]es, to be considered. All failures must be examined which could have occu[illegible] [illegible]eviously, as well as all failures which might occur during the Flight [illegible] being analyzed. For example, failure of the wings to sweep forward during descent would require consideration of a wings-aft landing that otherwise would never be encountered. There are failures that would always result in an aborted mission. The pertinent Flight Phase after such failures would be those required to complete the aborted (rather than the planned) mission. For example, failure of the flaps to retract after takeoff [illegible] [illegible] landing with flaps at the takeoff setting, with certain unexpended external stores.

The results of the analyses of vehicle flying qualities/flight safety may be used directly to: a) establish flight test points that are critical and should be emphasized in the flight test program, b) establish operator training requirements for the most probable and the critical failure conditions, and c) provide guidance and requirements for other subsystem designs. Proof

of compliance is, for the most part, analytical in nature as far as probabilities of failure are concerned. However, some equipment failure rate data may become available during final design phases and during flight test, and any data from these or other test programs should be used to further demonstrate compliance. Stability and control data of the usual type e.g., predictions, wind tunnel, flight test) will also be used to demonst. te compliance. Finally, the results of all analyses and tests will be subje t to normal procedures of procuring agency approval.

Specific Failures (3.1.9.2.4): Although present specific failure requirements may not yet appear in this preliminary RPV criteria it would seem to be highly probable that there will be some specific requirements pertaining to failure of the engines and the flight control system. For these requirements the specific failure is assumed to occur (with a probability of 1) with other failures considered at their own probabilities. For all other require nts, the actual probabilities of engine and flight control system failure are to be accounted for in the same manner as for other failures.

Special Failures: Note that certain Special Failure States (3.1.6.2.1) may be approved; these Failure States need not be considered in determining the probabilities for 3.1.9.2.1 and 3.1.9.2.3. This allows each failure possibility to be considered on its own. Requiring approval for each Special Failure State gives the procuring activity an opportunity to examine all the pertinent survivability and vulnerability aspects of each design.

3.2 MISSION PERFORMANCE REQUIREMENTS

REQUIREMENT

3.2 Mission Performance Requirement. The RPV system shall meet the mission performance requirements specified in this section.

The procuring activity shall clearly identify in this section the mission flight phase performance requirements by:

- o Stating, where feasible, Flight Phase performance requirements in terms of capabilities, limits, and accuracies required to meet the mission flight phase task, or
- o Identifying applicable performance and operational requirements within this specification, the vehicle specification or other system performance specifications.

DISCUSSIONS

In discussing the mission performance requirements of 3.2, it seems appropriate to summarize, for perspective, the organization and the relative hierarchy of the six subsections under Requirements (Figures 1 and 2).

3.1 General. Defines the conditions under which the requirements are to be applied.

3.2 Mission Performance Requirements. Mission flight phase performance requirements which the RPV system must satisfy.

3.3 System Requirements. Automatic and manual system-level requirements which include the combined operational characteristics of vehicle, data link, and control station.

3.4 Vehicle	Additional requirements to insure that these
3.5 Data Link	subsystems do not limit the total system
3.6 Control Data	capabilities in meeting requirements of 3.2 and/or 3.3

The organization of the RPV flying qualities criteria differs from that of MIL-F-8785B or MIL-F83300 in that it provides for defining mission, system, and subsystem requirement in a hierarchy fashion. The mission performance section (3.2) is intended to serve the following purposes:

(1) Identify performance parameters and/or values which the procuring activity should consider when defining the

performance requirements for the particular RPV system being designed.

(2) Provide a focal point within the requirements (guarantees) which the contractor must satisfy. To accomplish this the procuring activity must clearly identify in Section 3.2 the performance and operational requirements of this specification or other related performance specifications which are to apply.

(3) The mission requirements of 3.2 represents the highest level in the requirement hierarchy which must be satisfied. When such performance has been adequately established or demonstrated, but some related system requirement in 3.3 through 3.6 remains in question, the latter requirement may be relaxed if agreed upon by the procuring activity. The purpose is to avoid possible sacrifices in performance for the sake of meeting a particular subsystem requirement. Consistency in requirements are a necessity; however, it is impossible to account for all peculiarities that may arise in the spectra of mission, control method, and vehicle characteristics.

These overall mission level performance requirements apply to whatever method of control is to be used (manual or automatic). It is anticipated that these requirements will be of two general types:

1. Requirements which directly state specific performance values; and

2. Requirements that identify performance parameters and conditions which will be considered by the procuring activity for specification. These types of requirements provide guidelines to insure that the significant performance factors have been considered in specifying the mission performance requirements.

The former apply to the more standard mission flight phase functions which can be generally defined by performance values (e.g. landing touchdown dispersions for conventional runways). The latter requirement is expected to represent the bulk of the mission performance requirements given in Section 3.2, since many performance areas are highly dependent on the mission and systems involved (e.g., weapon delivery).

A preliminary review of mission performance requirements during this study indicates four relatively common performance areas. These are position,

altitude, velocity (airspeed/ground speed), and attitude/heading accuracies. It would be desirable to group performance requirements by flight phase categories as illustrated below:

FLIGHT PHASE CATEGORY	LEVEL	PERFORMANCE ACCURACIES			
		POSITION	ALTITUDE	ATTITUDE	VELOCITY
A	1 2 3				
B	1 2 3				
C	1 2 3				
D	1 2 3				

However, the general conclusion of this study is that performance requirements are, in many cases, highly unique to the operational task and should be specified individually using parameters meaningful to each particular flight phase task. For example, although the above performance characteristics are generally implied in approach and landing tasks for Category C and D, they are usually described in terms of glide slope accuracies and touchdown dispersions. In addition, many flight phase tasks within the same category will require emphasis on different performance parameters and system conditions. Thus, the selected organization of section (3.2) is by Flight Phase Categories, with specific performance requirements by flight phase task.

A few example requirements are given in Sections 3.2.1 through 3.2.4. Section 3.2.1 refers to general overall mission performance requirements. The remaining sections relate to the four Flight Phase Categories specified in 1.4, and identify example mission performance requirements by Flight Phase. At the present time, these requirements can only be stated in a general manner - because of the lack of performance data. More detailed follow-on studies and further collection of data are required before actually establishing numerical performance requirements.

REQUIREMENTS

3.2.1 General Mission Requirements.

3.2.1.1 Performance Reliability. The overall mission completion reliability (R_M) and the overall vehicle reliability (R_V) will be specified by the procuring activity. The vehicle failure requirements (3.1.9.2.2 and 3.1.9.2.3) shall comply with these reliability values.

3.2.2. Category A Flight Phase Performance.

3.2.2.1 Terrain Following. The terrain following control mode shall be capable of maintaining the vehicle within the specified altitude Above Ground Level (AGL), with a probability of (to be specified). This performance shall be obtained while including the effects of accuracies and performance variations associated with the terrain following system, sensors, critical vehicle normal states, atmospheric conditions, and maneuvering attitudes.

3.2.2.2 Formation Flying. The RPV system shall be capable of maintaining a separation distance between vehicles of (to be specified) ft. with a (to be specified) percent probability.

3.2.2.3 Weapon Delivery. The procuring activity shall specify the performance requirements.

3.2.2.4 Surface Surveillance, Reconnaissance and Tracking. The RPV shall be controlled to hold specified ground track (course), altitude, and airspeed, accuracies for the period necessary to complete the mission flight phases.

Some sensors may impose additional altitude, attitude rate limits, and damping requirements on the vehicle.

3.2.3 Category B Flight Phase Performance.

3.2.3.1 Enroute Navigation. The method used for guidance and navigation shall maintain the vehicle within the position, altitude, and airspeed accuracies specified for the mission flight plan to assure achievement of mission performance guarantees.

3.2.4 CATEGORY C&D FLIGHT PHASE PERFORMANCE

REQUIREMENTS

3.2.4 Category C&D Flight Phase Performance. The launch and recovery performance stated under 3.2.4 shall be met for the following launch/recovery site requirements, and operational variations expected to occur in normal service.

- Launch/Recovery Site Requirements
  - Vertical/lateral terrain clearance boundaries
  - Runway/surface gradient
  - Ground interface (e.g., automatic landing system use
  - Takeoff/land distance
  - Landing velocity limits (e.g., arresting gear, net capture)
  - Parachute recovery envelope

- Operational Variations
  - The most critical normal vehicle state (3.1.6.1)
  - Approach speed and glide slopes
  - Wind/turbulence conditions

3.2.4.1 Approach. The RPV shall be capable of acquiring the required glide slope and azimuth track within the performance accuracies and probabilities specified. Methods for specifying the performance should consider the following:

- Glide path/azimuth overshoot at capture
- Response stability (damping ratio)
- Glide slope/azimuth tracking dispersions
- Position accuracies at specific approach points (e.g., 100 ft altitude)
- Velocity

3.2.4.2 Landing. The RPV shall be capable of achieving touchdown position dispersions and velocity limits specified for the particular method of recovery.

Touchdown accuracies for conventional and arresting gear landings should be specified in terms of longitudinal and lateral touchdown dispersions. Position accuracies for vertical net type captures will be specified in terms of lateral and vertical dispersions from the center of the net. Vertical and lateral velocity limits shall be identified to insure that the landing loads are within the landing gear design limits. Landing speed limits will be required for arresting gear and net captures. Touchdown dispersions should be related to a statistical probability (i.e., 2σ or 3σ).

During ground rollout for conventional landing, it shall be possible to control the RPV to a full stop or ground speed appropriate for taxiing within the landing distance and lateral dispersions specified for the landing site.

3.2.4.3 Landing Abort/Go-Around. When a wave-off/go-around Flight Phase is specified, the vehicle shall be capable of executing this maneuver from a minimum decision altitude agreed upon by the procurement activity and contractor. The vehicle shall be able to clear the vertical obstacle profile and remain with the lateral boundaries witn the probabilities specified by the procuring activity.

DISCUSSION

Minimum decision altitude will be based on a high probability that the vehicle will not incur structural damage during the go-around. The actual decision altitude will depend on the RPV design. Two requirement philosophies are possible: the decision altitude is specified by the procuring activity and the vehicle must be designed to meet it, or the altitude may be established by the contractor during design. It must be remembered that although this is not a piloted vehicle, safety and performance reliability is important at the recovery site.

3.3 SYSTEM REQUIREMENTS

GENERAL DISCUSSION

Section 3.3 identifies more detailed total system requirements for various flight control functions and operation characteristics. These requirements are to be satisfied while including the combined operational characteristics and interfaces of vehicle, data link, and control station, as applicable. The organization of this section is as follows:

3.3.1 Automatic Control

3.3.2 Manual Control

3.3.3 Stability Margins

3.3.4 Operation and Interface

3.3.5 Atmospheric Disturbances

The Automatic Control Section specifies AFCS performance for individual flight control functions (3.3.1.1), such as attitude hold, airspeed hold, etc.; and for guidance functions (3.3.1.2) which involve vehicle steering from guidance and control systems, such as automatic landing. In general, these AFCS requirements are stated in terms of performance requirements. The Manual Control Section (3.3.2) deals with system parameters and response characteristics which the operator requires to perform the flight phase task manually. Many of the manual control requirements are associated with the 'pilot rating scale', which in turn, establishes the acceptable parameter ranges for the three flying quality levels.

Section 3.3.3 deals with stability margins (gain and phase margins) for all aerodynamic flight control system loops. The intent of the two requirements in this section is to offer two approaches: Satisfy specific gain and phase margin requirements, or establish gain and phase margins based on a sensitivity analysis of loop tolerances, accuracies, etc.

The Operations and Interface requirements deal with such conditions as engagement, disengagement transients, mode logic, etc. Finally, the Atmospheric Disturbance Section contains the wind, turbulence and gust models to be used when determining compliance with those requirements which involve stated atmospheric conditions.

3.3.1 AUTOMATIC CONTROL

REQUIREMENT

3.3.1 Automatic Control.

GENERAL DISCUSSION

The automatic control mechanization requirements are divided into flight control functions and guidance functions. The flight control section (3.3.1.1) specifies performance (accuracy) requirements for individual flight control functions such as attitude hold, airspeed hold, etc. These functions may be used to provide operator assist (relief) during manual control or become elements of a automatic flight control guidance loop. The guidance section (3.3.1.2) specifies requirements which apply to those AFCS functions which provide flight path control in accordance with steering signals generated by guidance and control systems.

In general, both the flight control and guidance function sections state performance requirements. The flight control requirements identify accuracy requirements for individual flight control functions. The guidance section specifies requirements which the AFCS shall satisfy to perform particular flight phase guidance tasks. In some cases, the guidance functions may specify additional requirements on the individual flight control functions involved, in order to be compatible with particular performance requirements, guidance functions, methods, or systems selected. In any event, the flight control requirements of 3.3.1.1 should not limit the capability of the AFCS in meeting the guidance mission-performance requirements of 3.3.1.2.

The automatic control performance requirements of 3.3.1.1 and 3.3.1.2 may also be interpreted as mission flight phase performance requirements, particularly the AFCS guidance functions in 3.3.1.2 When dealing with AFCS functions, the overall mission performance requirements specified in 3.2 shall be met. Section 3.2 may even reference particular requirements in 3.3.1.2 or other requirements in this specification. However, in the absence of specified AFCS performance (either in Section 3.2, or other detail performance specifications), the applicable requirements of 3.3.1 will be used.

3.3.1.1 FLIGHT CONTROL REQUIREMENTS

REQUIREMENTS

3.3.1.1 Flight Control Requirements. When the following AFCS functions are used, the following specified performance shall be provided. Unless otherwise specified, these requirements apply in smooth air and include sensor error. Except where specified, a damping ratio of at least (to be determined) shall be provided for nonstructural AFCS-controlled mode responses. Specified damping requirements apply only to the response characteristics for perturbations at least an order of magnitude greater than the allowable residual oscillation. These requirements apply to automatic flight control functions which may also be used as operator assist modes to manual control. When these flight control functions are part of an automatic guidance function, the requirements of 3.3.1.2 apply.

3.3.1.1.1 Attitude Hold (Pitch and Roll). Attitudes shall be maintained in smooth air with a static accuracy of $\pm$ 0.5 degree in pitch attitude (with wings level) and $\pm$ 1.0 degree in roll attitude with respect to the reference. Allowable RMS deviations in pitch and roll for turbulence models are (to be determined). These accuracies shall apply to automatic attitude hold functions which either maintain the vehicle attitude, or return the vehicle to a wings-level attitude at the time manual-control maneuver inputs are removed.

3.3.1.1.1.1 Pitch Transient Response. The short-term pitch response shall be smooth and rapid. When the automatic flight control attitude hold function is intended to return the vehicle to a reference attitude after manual overrides which change the pitch attitude by at least $\pm$ 5 degrees, the vehicle shall return to the reference attitude within one overshoot which shall not exceed 20 percent of the initial deviation. The period of overpowering shall be short enough to hold the airspeed change to within 5 percent of the trim airspeed.

3.3.1.1.1.2 Roll Transient Response. The short-term roll response shall be smooth and rapid. When the automatic flight control attitude hold function is intended to return the vehicle to a reference attitude after manual overrides which reach a bank angle of approximately 20 degrees, the vehicle shall return to the initial roll attitude within one overshoot which shall not exceed 20 percent of the initial deviation.

3.3.1.1.2 Heading Hold. In smooth air, when the heading hold is engaged, the automatic flight control system shall maintain the vehicle at its existing heading within a static accuracy of $\pm$0.5 degree with respect to the gyro accuracy. Allowable RMS deviations for turbulence models are (to be determined).

3.3.1.1.3 Heading Select. When an automatic heading selection system is used the automatic flight control system shall automatically turn the vehicle through the smallest angle (left or right) to a heading either automatically or manually selected and maintain that heading as in the heading hold mode. The heading select shall have 360 degrees of control. The bank angle while turning to the selected heading shall provide satisfactory turn rates and preclude impending stall. If used as an assist mode in manual control the operator shall be able to select bank angle by control inputs and then remove the command. The aircraft shall not roll in a direction other than the direction required for the vehicle to assume its proper bank angle. In addition, the roll-in and roll-out shall be accomplished smoothly with no disturbing variation in roll rate.

3.3.1.1.3.1 Transient Response. Entry into and termination of the turn shall be smooth and rapid and the aircraft shall not overshoot the selected headings by more than 1.5 degrees.

3.3.1.1.3.2 Altitude Coordinated Turns. It shall be possible to maintain altitude within the accuracies specified in Table 6 during coordinated turns in either direction, for the maximum pitch, roll, yaw maneuvering attitudes.

3.3.1.1.4 Altitude Hold. Engagement of the altitude hold function at rates of climb or descent less than 2000 fpm shall select the existing indicated (sensed) altitude and control the vehicle to this altitude as a reference. For engagement at rates above 2000 feet per minute the AFCS shall not cause any unsafe vehicle maneuvers. Within the vehicle thrust-drag capability and at steady bank angles, this function shall provide control accuracies shown in Table 6.

TABLE 6. MINIMUM ACCEPTABLE CONTROL ACCURACY

BANK ANGLE (DEG.) / ALT. (FT.)	0 - 1	1 - 30	30 - 60
55,000 to 80,000	±0.1% at 55,000 varying linearly to ±0.2% at 80,000	±60 ft. or ±0.3% whichever is larger	±90 ft. or ±0.4% whichever is larger
30,000 to 55,000	±0.1%		
0 to 30,000	±30 ft.		

These accuracy requirements apply for airspeeds up to Mach 1.0. Double these values are permitted above Mach ..0 and triple these values apply above Mach 2.0. Any periodic residual oscillation within these limits shall not interfere with mission flight phase performance requirements or operator's ability to perform the flight phase task.

3.3.1.1.5 Mach Hold. The Mach number existing at the engagement of Mach hold shall be the reference. After engagement and stabilization on Mach hold, the AFCS shall maintain indicated Mach number and error shall not exceed $\pm$0.01 Mach or $\pm$2 percent of indicated Mach, whichever is larger, with respect to the reference. Any periodic oscillation within these limits shall not interfere with mission performance or operator ability to perform task. The contractor shall establish a maximum response time to capture requirement which is suitable for the mission phase.

3.3.1.1.6 Airspeed Hold. The airspeed existing at the engagement of Airspeed Hold shall be the reference. Indicated airspeed shall be maintained within $\pm$5 knots or $\pm$2 percent, whichever is greater, of the reference airspeed. Any periodic oscillation within this limit shall not interfere with mission performance or operator's ability to perform task. The contractor shall establish a maximum time to capture requirement which is suitable for the mission phase.

DISCUSSION

The requirements of this section are essentially taken from MIL-F-9490D and MIL-C-18244A, and need to be evaluated in more detail for RPV use. Some of these requirements may be too severe for some RPV's since identification by mission flight phase and class of vehicle has not been made. However, these requirements are based on an extensive aircraft background, and are felt to be generally applicable to RPV's unless otherwise specified by the procuring activity.

The AFCS performance specified in this Section is intended to include "not-to-exceed" parameters which are felt necessary for proper operation. Operator relief functions are specified to reduce operator fatigue to a level consistent with general mission requirements. Performance is generally specified with respect to sensor indicated values. In many cases, sensor accuracy is set by manual control considerations. Where performance is not specified with respect to an FCS sensor reference, sensor error must be included in meeting the requirement.

In some instances references have been made to RMS deviations in the wind turbulence model which is to be specified by the procuring activity. Future development of criteria should establish RMS values for specific turbulence wind models which would be identified in Section 3.3.5. It is expected that RMS values given in MIL-F-8785B and MIL-F-9490D may also apply for RPV's.

3.3.1.2 AUTOMATIC GUIDANCE REQUIREMENTS

REQUIREMENTS

3.3.1.2 Automatic Guidance Requirements. These requirements apply to those control functions which provide automatic flight path control in accordance with steering signals generated by guidance and control systems.

During automatic guidance operations, the flight control function of 3.3.1.1 become elements within the guidance loop. The overall performance requirements which this combination shall meet are the mission flight phase performance requirements of 3.2 and any detailed system performance requirements specified by the procuring activity. When specific performance requirements have not been established in 3.2, the following applicable requirements shall be met.

DISCUSSION

This section applies to the following types of guidance control functions:

Enroute Navigation

Rendezvous and Station Keeping

Guidance Steering for Weapon Delivery

Sensor Following Modes

Search and Tracking

Automatic Terrain Clearance Avoidance

Approach and Landing

Takeoff

The specific AFCS guidance requirements are unique to the particular guidance method, sensors, and mission function involved. In some instances these requirements will identify complementary AFCS performance requirements for interface with specific guidance systems and/or reflect the operational practice and procedures. As the RPV operation develops, the methodology and data will be established for specifying requirements for specific guidance systems and practices used in RPV operations.

The requirements presented in this section apply unless specific AFCS performance requirements have been specified in Section 3.2.

This approach to the AFCS guidance requirments is similar to those of MIL-F-9490D (USAF) and MIL-C-18244A (Navy). For example, MIL-F-9490D identifies

AFCS requirements relative to VOR/TACAN navigation, capture, and tracking; and localizer and glide slope for automatic instrument approach systems. The Navy specification identifies AFCS pitch, lateral, and airspeed control requirements for interface with the AN/SPN-10 landing system.

3.3.1.2.1 AUTOMATIC LANDING AND APPROACH

REQUIREMENTS

3.3.1.2.1 Automatic Approach and Landing System. The approach mode of the AFCS shall respond to azimuth/localizer signals as required for lateral guidance and glide slope signals for vertical guidance. The system shall be automatically capable of steering the aircraft to a minimum height of 100 ft. when manual control is specified as the primary landing mode, or shall automatically control the aircraft through touchdown and roll-out when a fully automatic landing system has been specified.

The system shall provide timely warning to permit the operator to execute the landing or a go-around maneuver following a failure in the automatic landing system.

The system shall comply with the landing performance requirements of this section while including the effects of the following variations unless otherwise stated in the following individual requirements:

- Landing weight and center of gravity
- Flap position
- Approach speed and approach angle
- Glide slope and localizer centering errors
- Tolerances associated with the AFCS in the guidance mode (i.e., sensors, computer, actuator vehicle augmentation tolerances)
- Switching transients
- Wind and turbulence models of 3.3.5
- Runway gradient and surface conditions

3.3.1.2.1.1 Localizer Mode - Capture, Track and Control. The AFCS guidance mode shall vector the vehicle to acquire the localizer beam on a heading angle of 45° or less at least 8 nautical miles from runway threshold. For these conditions, the overshoot shall not exceed 0.5 degrees in a no wind condition. During localizer capture, the response will be smooth and stable.

Following capture, the system will provide stable control and tracking along the approach path. The system will position the RPV, within $\pm$ 60 ft (2σ error) of the extended runway centerline at the 100 ft altitude.

3.2.1.2.1.2 Glide Slope Mode - Capture, Track, and Control. When satisfactory glide slope capture pre-conditions have been obtained (established by flight control design), the AFCS will automatically transition from its present longitudinal mode of control (e.g., altitude hold) to the glide slope capture mode. The glide slope capture, whether above or below the desired glide path shall be smooth and the first overshoot shall not exceed 0.3° from the nominal reference glide path for a no wind condition.

The AFCS glide slope mode shall provide stable tracking within ±0.20 degrees (2σ) and position the RPV in smooth air within a 2σ altitude error of $\pm$ 12 ft at the 100 ft reference altitude.

3.3.1.2.1.3 Automatic Touchdown Landings. This requirement pertains to the final approach stages below the minimum decision or alert height to touchdown. The automatic landing system shall continue to control the RPV along the glide slope, through a selected flare profile, if applicable, and shall limit the touchdown or recovery dispersions to those specified in 3.2. Unless otherwise specified, the conventional touchdown down dispersions in Table 7 for landing gear or skid landings shall be met with a 2σ probability of success.

3.3.1.2.1.4 Runway Alignment. The lateral-directional mode of the automatic landing system, in meeting the lateral position touchdown requirements of Table 7, shall insure that the combined vehicle lateral drift rates and touchdown alignments are within the operational side load design capability of the landing gear. The selection of a final alignment mode, if any, must be compatible with control response characteristics of the RPV.

3.3.1.2.1.5 Rollout. During rollout, the AFCS shall maintain 2σ runway centerline position alignments of $\pm$25 ft. Differential braking may be considered, when applicable, to maintain these alignments.

3.3.1.2.1.6 Go-Around Mode. When required, the automatic go-around mode shall be initiated automatically for specific failures agreed upon by contractor and procuring activity. The operator shall have the capability of manually engaging the go-around mode. A single control switch will engage all systems into their proper mode for go-around. In the event of AFCS failures which affect available control modes, the go-around mode will automatically sequence to the next most desirable mode of control.

The pitch AFCS shall smoothly rotate the vehicle to establish a positive rate of climb such that the vehicle will not intersect the obstacle clearance planes defined by the procuring activity.

The lateral heading AFCS shall maintain a 4σ vehicle position within the lateral boundaries of the obstacle planes during wind conditions defined in 3.3.5.

The minimum altitude for engaging automatic go-around shall be established such that the probability of incurring structural damage (landing gear, etc.) is

TABLE 7. DISPERSION AT TOUCHDOWN (95% PROBABILITY)

VEHICLE CLASSIFICATION (SECTION 1.4)	VEHICLE TYPE	TOTAL LONGITUDINAL DISPERSION	LATERAL DISPERSION
II	Compass Cope*		
	With Flare	1,000 ft.	
	Without Flare	200 ft.	
III	Droned Manned Aircraft*		
	With Flare	1,500 ft.	
	Without Flare	200 ft.	
	Multi-Mission Vehicles*		
	With Flare	1,500 ft.	±23 ft.
	Without Flare	200 ft.	
	Advanced RPV (MSD Rockwell Design)		
	Without Flare (Arrested landing)	300 ft.	±25 ft.

*Data from Reference 7.

extremely remote. This minimum altitude shall include normal performance under wind conditions in 3.3.5.

3.3.1.2.2 Automatic Takeoff Systems. These requirements apply to the ground roll, and climb out. This mode shall be manually engaged only, and only after all pre-takeoff conditions have been satisfied.

3.3.1.2.2.1 Ground Roll. During ground roll, the AFCS shall maintain the RPV in firm contact with the runway and in a stable attitude. Lateral displacement from the runway center line shall be the same as specified in 3.3.1.2.1.5 for rollout.

3.3.1.2.2.2 Climb Out. The rotation or lift-off maneuver appropriate for the particular RPV will be initiated automatically when the proper designated airspeed has been obtained. During initial climbout, the RPV will maintain a wings-level altitude; transition to control modes involving bank angles will not be initiated below 50 ft.

DISCUSSION

The automatic approach and landing requirements of 3.3.1.2.1 and automatic takeoff requirements of 3.3.1.2.2 are based on MIL-F-9490D and an RPV automatic takeoff and landing requirements study (Reference 7). Both documents, in most cases, state similar performance values when dealing with like requirements. The stated performance values of Reference 7, are given as either extensions of or modifications to the performance specification defined in FAA Advsiory Circulars 20-57A, 120-28A, and 120-29 which establish automatic landing system performance for commercial carrier operations. In addition, Reference 7 used existing AFFDL analytical facilities to briefly examine the applicability of FAA criteria to RPV operations.

Obviously, the touchdown dispersions of Table 7 are not presented in the best form for a specification; particularly when referencing specific vehicle designs. The present intent is to serve as a data base. Touchdown requirements with and without flare should be distinguished separately. Landing dispersions involving a flare profile will be significantly larger than with a direct fly-in approach.

3.3.1.2.3 AUTOMATIC NAVIGATION SYSTEM
3.3.1.2.4 TERRAIN FOLLOWING SYSTEM

REQUIREMENT

3.3.1.2.3 Automatic Navigation System. The navigation mode of the AFCS shall respond to position, airspeed, and altitude errors, to maintain the vehicle within the accuracy requirements of mission flight plan. Allowable position errors will be specified by the procuring activity.

Unless specified in the mission performance of 3.2, the airspeed and altitude performance shall meet the requirements of 3.3.1.1.4 through 3.3.1.1.6.

3.3.1.2.4 Terrain Following System. When a low-altitude terrain-following system is required, the AFCS terrain-following/avoidance mode shall be capable of providing a low probability of ground clobber at the minimum altitude Above Ground Level (AGL) specified by the mission performance requirements of 3.2.

When not otherwise specified, the RPV shall be capable of flying at a minimum altitude of 250 ft. AGL with a 2σ altitude tolerance of ± 100 ft. These conditions shall be met for all maximum attitude combinations (pitch, roll and yaw).

DISCUSSION

This requirement is intended to insure that under normal operation the expected performance variations of the terrain following system are within limits which insure that the altitude AGL can be successfully maintained with a high probability of success.

A terrain following system is normally used to avoid detection and minimize radar exposure. The values stated are estimated and require further study; however, it is felt they are representative of maximum requirements for a terrain following system.

3.3.2 MANUAL CONTROL

GENERAL DISCUSSION

The manual control requirements of 3.3.2, like those for automatic control (3.3.1), deal with the characteristics of the total system (control station, data link, and vehicle). The manual flying quality requirements of Section 3.3.2 are directed at the total system stability and dynamic response characteristics which the operator likes or requires to do the job rather than performance. The flying qualities levels involved are directly associated with a 'pilot rating scale' which in turn, establishes acceptable parameter ranges for each of the three flying quality levels.

The preliminary requirements of this section are given under two major categories: Longitudinal Response Characteristics (3.3.2.1) and Lateral-Directional Response Characteristics (3.3.2.2). The criteria, as stated in this document, reflect the basic or classical response characteristics as defined for piloted aircraft and are essentially taken from MIL-F-8785B. Table 8 summarizes the principal flying qualities parameters considered and the general nature of the requirements. The requirements within this section have been cross-referenced to the equivalent sections of MIL-F-8785B. This provides a reference for those readers who will be trying to draw parallels between the two documents. Much of the material in MIL-F-8785B is generally applicable as background to this document, especially the theoretical development of the handling qualities parameters. These discussions have not been included in this document; the reader is referred to Reference 2.

The intent of these requirements is to provide a beginning framework or starting point for follow-on development of RPV requirements. The RPV stability and response requirements for manual control are expected to be different from those for piloted aircraft. The limitations of the visual displays (lack of peripheral cues), and the absence of direct kinesthetic motion cues are expected to result in different, if not more restrictive, limitations on the stability and response parameters for manual control. However, the limited published results available in the literature do not permit redefinition of new flying qualities parameters or values at this time.

Further, although these preliminary requirements presently reflect the conventional approach used in flying qualities specifications, these requirements should be interpreted in terms of total response requirements for an equivalent classical system (with response matched reasonably well over the pertinent frequency range), and not to any particular roots when higher-order system roots also influence the response. It has to be recognized that in some cases the flying qualities parameters, taken from the classical airframe transfer functions, may not adequately describe the dynamic response. These transfer functions do not consider the additional effects of complex control inputs. In many cases the control loop dynamics are sufficiently 'fast', compared to the basic vehicle response, that they may be neglected because their

TABLE 8. SUMMARY OF CLASSICAL FLYING QUALITIES PARAMETERS.

PARAMETER	NATURE OF MIL-F-8785B REQUIREMENTS
Longitudinal Dynamics	
Short Period (Maneuver) Response:	
-Frequency ($\omega_{n_{s_p}}$)	Frequency limits are a function of $\frac{n}{\alpha}$ (g's per angle of attack)
-Damping (ζ_{s_p})	Damping ranges specified
Phugoid (Long Term) Response:	
-Frequency (ω_{n_p})	---
-Damping (ζ_p)	Minimum damping limits
Lateral - Directional	
Dutch Roll:	
-Frequency (ω_{n_d})	Minimum Frequency and damping limits - function of ϕ/β ratio
-Damping (ζ_d)	
Roll Subsistence Mode:	
-Time Constant (τ_R)	Maximum roll time constant limits
	Roll response requirements (degrees in so many seconds)
Spiral Divergence	
-Time Constant (τ_s)	Limit on divergence

effect is minimal. In these situations, the handling/flying qualities can be adequately described by the classical vehicle (airplane) transfer functions. This, in general, has been the approach taken in interpreting the airplane flying quality requirements of MIL-F-8785B. That is, the combination of control system dynamics, augmentation and vehicle parameters is to provide the longitudinal and lateral-directional response characteristics specified in MIL-F-8785B. This extrapolation is normally satisfactory as long as the actual response characteristics are representative of the transfer functions upon which the requirements were initially established. However, it is possible that a remote operator will not be subjected to the more conventional airplane-like response due to coupling of complex control system dynamics, augmentation, data link, etc.

It is necessary that the follow-on studies establish an equivalent system model and define flying quality parameter requirements which will permit extension of the more classical requirements to include higher order systems. One example of an equivalent systems approach is discussed in Reference 8.

The criteria as presently stated in this section contain the same flying quality parameters, figures and tables as given in MIL-F-8785B and will have to be evaluated and updated to conform with the RPV Vehicle Classes, Flight Phase Categories, and Levels; and to include new or modified flying quality parameter requirements which are more meaningful to RPV's. This approach was necessitated by the almost complete lack of pertinent, applicable RPV data in the open literature.

3.3.2.1 LONGITUDINAL RESPONSE CHARACTERISTICS
3.3.2.1.1 SHORT TERM RESPONSE
3.3.2.1.2 LONGITUDINAL STABILITY WITH RESPECT TO SPEED

REQUIREMENTS

3.3.2.1 Longitudinal Response Characteristics.

3.3.2.1.1 Short-Term Response. The short-term response of angle of attack which occurs at approximately constant speed, and which may be produced by abrupt control inputs, shall meet the requirements of 3.3.2.1.1.1 and 3.3.2.1.1.2. These requirements apply with controls free or fixed, for responses of any magnitude that might be experienced in service use. If oscillations are nonlinear with amplitude, the requirements shall apply to each cycle of the oscillation. In addition meeting the numerical requirements of 3.3.2.1.1.1 and 3.3.2.1.1.2, the contractor shall show that the vehicle has acceptable response characteristics in atmospheric disturbances (to be specified in 3.3.5).

3.3.2.1.1.1 Short Term Frequency and Acceleration Sensitivity. The short-term undamped natural frequency, $\omega_{n_{SP}}$, shall be within the limits shown in Figures 11, 12, and 13. If suitable means of directly controlling normal force are provided, the lower bounds on $\omega_{n_{SP}}$ and n/α of Figure 13 may be relaxed if approved by the procuring activity.

3.3.2.1.1.2 Short Term Damping. The short-term damping ratio, ζ_{SP}, shall be within the limits of Table 9.

TABLE 9. SHORT-TERM DAMPING RATIO LIMITS

Level	Category A and C Flight Phases		Category B and D Flight Phases	
	Minimum	Maximum	Minimum	Maximum
1	0.35	1.30	0.30	2.00
2	0.25	2.00	0.20	2.00
3	0.15		0.15*	

*May be reduced at altitudes above 20,000 feet if approved by the procuring activity.

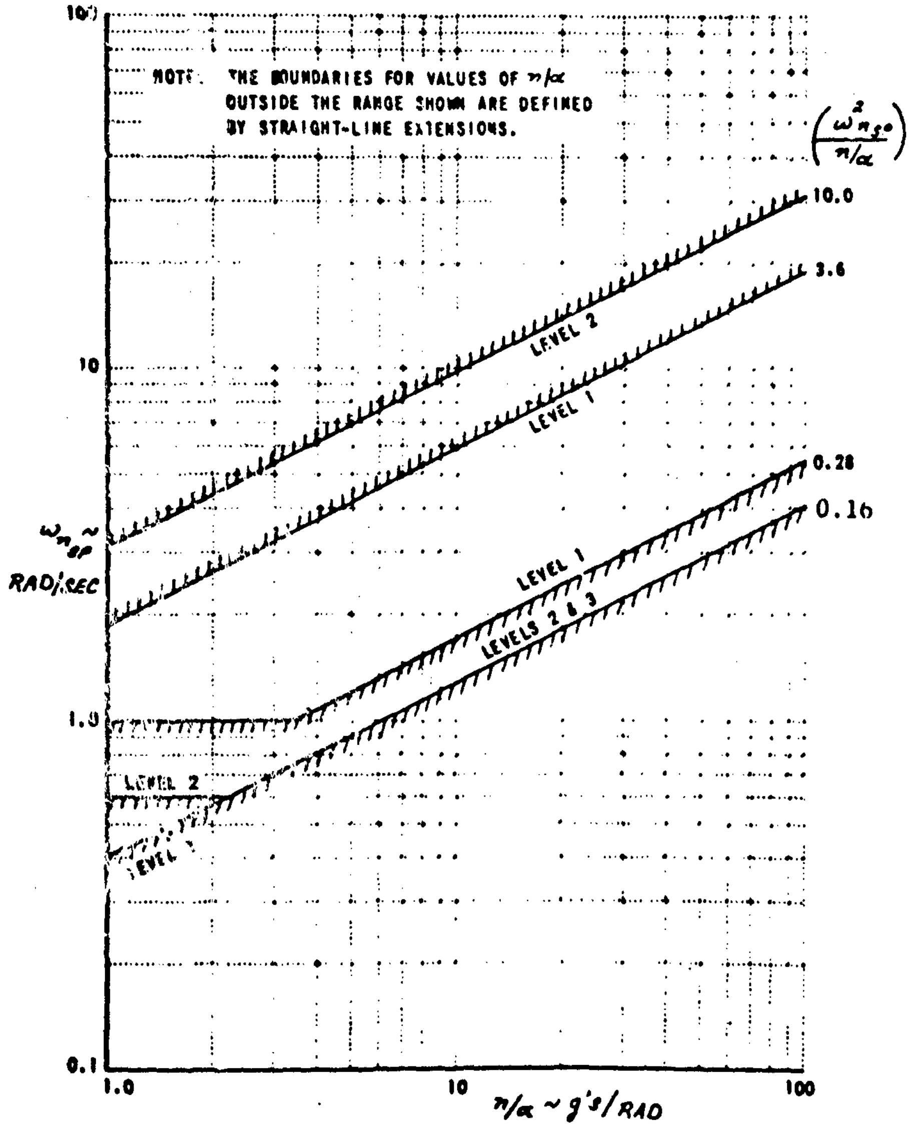


Figure 11. Short-Period Frequency Requirements-Category A Flight Phases

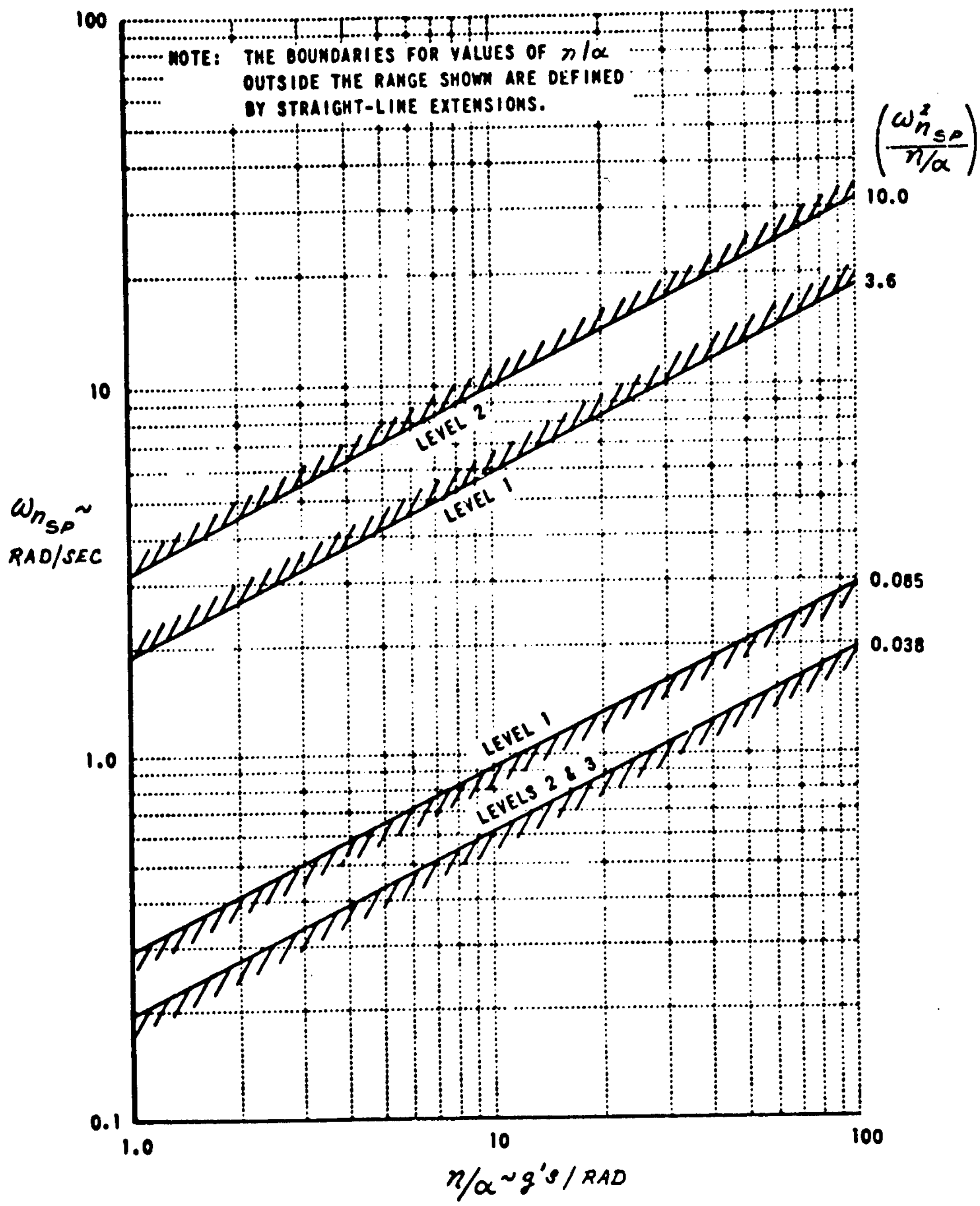


Figure 12. Short-Period Frequency Requirements-Category B Flight Phases

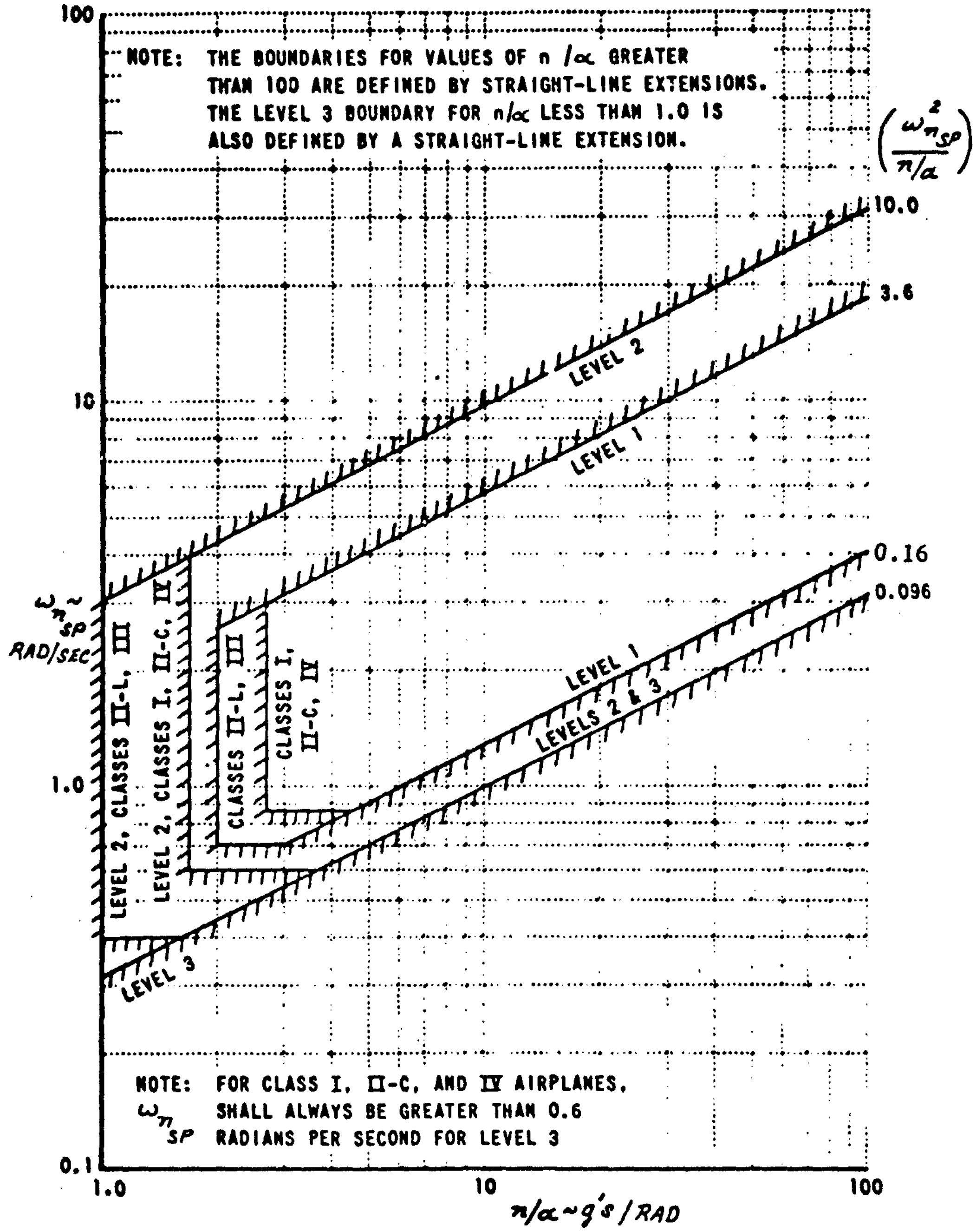


Figure 13. Short-Period Frequency Requirements-Category C Flight Phases

3.3.2.1.2 Longitudinal Stability With Respect To Speed.

3.3.2.1.2.1 Longitudinal Static Stability. There shall be no tendency for the airspeed to diverge aperiodically when the vehicle is disturbed from trim with the controls fixed and with them free. This requirement will be considered satisfied if the variations of control force and position with airspeed are smooth and the local gradients stable, with:

Trimmer and throttle controls not moved from the trim settings by the operator, and

1g acceleration normal to the flight path, and

Constant altitude

over a range about the trim speed of ± 15 percent or ± 50 knots equivalent airspeed, whichever is less (except where limited by the boundaries of the Service Flight Envelope). Stable gradients mean increasing aft motion of the controller to maintain slower airspeeds and the opposite to maintain faster airspeeds. The term gradient does not include the portion of the controller force or position versus airspeed curve within the breakout or friction range.

3.3.2.1.2.2 Phugoid Stability. The long-term airspeed oscillations which occur when the vehicle seeks a stabilized airspeed following a disturbance shall meet the following requirements:

a. Level 1 ------ ζ_p at least 0.04

b. Level 2 ------ ζ_p at least 0

c. Level 3 ------ T_2 at least 55 seconds.

These requirements apply with the longitudinal control free and also with it fixed.

3.3.2.1.2.3 Flight-Path Stability. Flight-path stability is defined in terms of flight-path-angle change where the airspeed is changed by the use of the longitudinal control only (throttle setting not changed by the operator). For the landing approach Flight Phase, the flight-path-angle versus true-airspeed curve shall have a local slope at $V_{o_{min}}$ which is negative or less positive than:

a. Level 1 ------ 0.06 degrees/knot

b. Level 2 ------ 0.15 degrees/knot

c. Level 3 ------ 0.24 degrees/knot.

The thrust setting shall be that required for the normal approach glide path at $V_{o_{min}}$. The slope of the flight-path angle versus airspeed curve at 5 knots slower than $V_{o_{min}}$ shall not be more than 0.05 degrees per knot more positive than the slope at $V_{o_{min}}$, as illustrated by Figure 14.

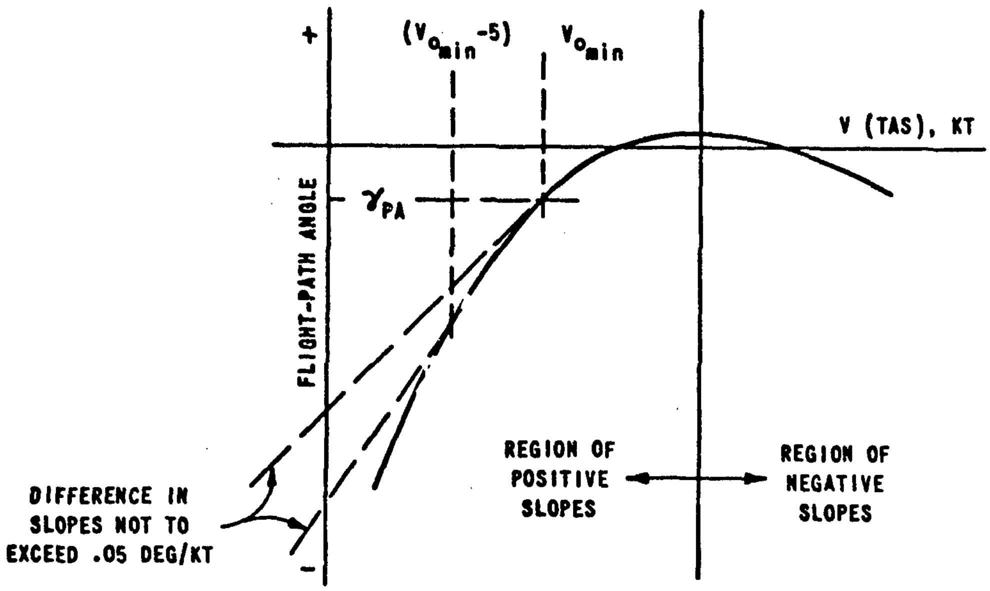


Figure 14. Flight Path Angle Versus Airspeed

DISCUSSION (Related MIL-F-8785B paragraphs 3.2.1 and 3.2.2)

The Longitudinal Response Characteristics (3.3.2.1) are presented under two major categories as in MIL-F-8785B. The flying quality characteristics dealing with the longitudinal short term response to rapid control inputs at essentially constant speed are grouped under Short Term Response (3.3.2.1.1). Subjects dealing with long term stability and response changes with respect to airspeed have been grouped under Longitudinal Stability with Respect to Speed (3.3.2.1.2). These divisions represents the two simplified classical approaches used in solving the equations of motion.

The requirements given in this document identify the major flying qualities parameters which are presently used in manned aircraft to describe the classical longitudinal response. These requirements are stated with the same

values as in MIL-F-8785B as there are no data to substantiate a change. The intent is to provide a starting point and guidelines from which to develop more useful RPV requirements. Follow-on studies should establish flying quality parameters and values for an equivalent total system model which would permit expanding the requirements to include higher order systems as discussed in 3.3.2. It is expected that such a study would start with the classical response parameters to determine which parameters presently used in MIL-F-8785B are most meaningful to RPV's. This would include questionable parameters such as n/α which are used in Requirement 3.2.1.1.1 to bound the short-term frequency response based on acceleration sensitivity of the vehicle. Both, References 9 and 10 looked at this parameter with somewhat inconclusive results. The opinion of Reference 9 was that acceleration parameters of this type may not be very useful for RPV's.

The vehicle classes indicated on Figure 13 are the aircraft classes of MIL-F-8785B. Appropriate limits for RPV vehicle classes remain to be established, provided the parameter, n/α, is a useful flying qualities parameter for RPV's.

3.3.2.2 LATERAL-DIRECTIONAL RESPONSE CHARACTERISTICS

REQUIREMENTS

3.3.2.2 Lateral-Directional Response Characteristics.

3.3.2.2.1 Lateral-Directional Oscillations (Dutch Roll). The frequency, ω_{n_d}, and damping ratio, ζ_d, of the lateral-directional oscillations following a rudder disturbance input shall exceed the minimums in Table 10. The requirements shall be met with controls fixed and with them free, in oscillations of any magnitude that might be experienced in operational use. If the oscillation is nonlinear with amplitude, the requirement shall apply to each cycle of the oscillation. Residual oscillations may be tolerated if the amplitudes are within the requirements of 3.3.3.3.

TABLE 10. MINIMUM DUTCH ROLL FREQUENCY AND DAMPING

Level	Flight Phase Category	Class	Min ζ_d*	Min $\zeta_d\omega_{n_d}$,* rad/sec.	Min ω_{n_d}, rad/sec.
1	A	I, IV II, III	0.19 0.19	0.35 0.35	1.0 0.4
	B	All	0.08	0.15	0.4
	C	I, II-C, IV	0.08	0.15	1.0
		II-L, III	0.08	0.15	0.4
2	All	All	0.02	0.05	0.4
3	All	All	0.02	-	0.4

*The governing damping requirement is that yielding the larger value of ζ_d.

When $\omega_{n_d}^2|\phi/\beta|_d$ is greater than 20 $(\text{rad/sec})^2$, the minimum $\zeta_d\omega_{n_d}$ shall be increased above the $\zeta_d\omega_{n_d}$ minimums listed above by:

Level 1 - $\Delta\zeta_d\,\omega_{n_d} = .014\,(\omega_{n_d}^2|\phi/\beta|_d - 20)$

Level 2 - $\Delta\zeta_d\,\omega_{n_d} = .009\,(\omega_{n_d}^2|\phi/\beta|_d - 20)$

Level 3 - $\Delta\zeta_d\,\omega_{n_d} = .005\,(\omega_{n_d}^2|\phi/\beta|_d - 20)$

with ω_{n_d} in rad/sec.

3.3.2.2.2 Roll Mode. The roll-mode time constant, τ_R, shall be no greater than the appropriate value in Table 11.

TABLE 11. MAXIMUM ROLL-MODE TIME CONSTANT

Flight Phase Category	Class	Level 1	Level 2	Level 3
A	I, IV	1.0	1.4	10
	II, III	1.4	3.0	
B	ALL	1.4	3.0	
C	I, II-C, IV	1.0	1.4	
	II-L, III	1.4	3.0	

3.3.2.2.3 Spiral Stability. The combined effects of spiral stability, flight control-system characteristics, and trim change with speed shall be such that following a disturbance in bank of up to 20 degrees, the time for the bank angle to double will be greater than the values in Table 12. This requirement shall be met with the airplane trimmed for wings-level, zero-yaw-rate flight with the cockpit controls free.

TABLE 12. SPIRAL STABILITY-MINIMUM TIME TO DOUBLE AMPLITUDE

Class	Flight Phase Category	Level 1	Level 2	Level 3
I & IV	A	12 sec	12 sec	4 sec
	B & C	20 sec	12 sec	4 sec
II & III	All	20 sec	12 sec	4 sec

3.3.2.2.4 Coupled roll-spiral oscillation. A coupled roll-spiral mode will not be permitted.

DISCUSSION

The lateral-directional criteria as presently stated contain the same flying quality parameters, figures and tables as given in MIL-F-8785B and will have to be evaluated and updated to conform with the RPV Vehicle Classes, Flight Phase Categories, and Levels; and to include new or modified flying quality parameter requirements which are more meaningful to RPV's. This approach was necessitated by the almost complete lack of pertinent, applicable RPV data in the open literature.

3.3.2.3 LATERAL-DIRECTIONAL CONTROL

3.3.2.3.1 ROLL CONTROL CHARACTERISTICS

REQUIREMENT

3.3.2.3 Lateral-Directional Control.

3.3.2.3.1 Roll Control Characteristics. There shall be no objectionable nonlinearities in the variation of rolling response with lateral control deflection or force. Sensitivity or sluggishness in response to small lateral control deflections or forces shall be avoided.

Roll control effectiveness shall be sufficient to meet the roll rate requirements of 3.6 as well as the bank angle vs. time requirements of Table 13.

DISCUSSION (Related MIL-F-8785B paragraphs 3.3.4, 3.3.4.3)

Roll control effectiveness is a maneuverability parameter of fundamental importance. A difficulty in attempting to specify realistic roll performance requirements in this general specification is that roll performance is probably more closely related to vehicle type and mission than most other characteristics. Table 13 summarizes minimum roll response for manned aircraft and was based on performance required to maneuver, and to encounter atmospheric disturbances, and on those aspects of roll performance requirements in MIL-F-8785 (1954) which did stand the test of time.

At this time requirements in Table 13 must be regarded as highly suspect for RPV's. It is questionable that such requirements can be realistically defined in such detail. Also, there are indicators (Reference 9, for example) that these numbers should be cut at least in half for RPV's.

TABLE 13. ROLL PERFORMANCE REQUIREMENTS

Class	Flight Phase Category	Level 1	Level 2	Level 3
I	A	ϕ_t = 60° in 1.3 sec	ϕ_t = 60° in 1.7 sec	ϕ_t = 60° in 2.6 sec
	B	ϕ_t = 60° in 1.7 sec	ϕ_t = 60° in 2.5 sec	ϕ_t = 60° in 3.4 sec
	C	ϕ_t = 30° in 1.3 sec	ϕ_t = 30° in 1.8 sec	ϕ_t = 30° in 2.6 sec
II	A	ϕ_t = 45° in 1.4 sec	ϕ_t = 45° in 1.9 sec	ϕ_t = 45° in 2.8 sec
II	B	ϕ_t = 45° in 1.9 sec	ϕ_t = 45° in 2.8 sec	ϕ_t = 45° in 3.8 sec
II-L	C	ϕ_t = 30° in 1.8 sec	ϕ_t = 30° in 2.5 sec	ϕ_t = 30° in 3.6 sec
II-C	C	ϕ_t = 25° in 1.0 sec	ϕ_t = 25° in 1.5 sec	ϕ_t = 25° in 2.0 sec
III	A	ϕ_t = 30° in 1.5 sec	ϕ_t = 30° in 2.0 sec	ϕ_t = 30° in 3.0 sec
	B	ϕ_t = 30° in 2.0 sec	ϕ_t = 30° in 3.0 sec	ϕ_t = 30° in 4.0 sec
	C	ϕ_t = 30° in 2.5 sec	ϕ_t = 30° in 3.2 sec	ϕ_t = 30° in 4.0 sec
IV	A	ϕ_t = 90° in 1.3 sec	ϕ_t = 90° in 1.7 sec	ϕ_t = 90° in 2.6 sec
	B	ϕ_t = 90° in 1.7 sec	ϕ_t = 90° in 2.5 sec	ϕ_t = 90° in 3.4 sec
	C	ϕ_t = 30° in 1.0 sec	ϕ_t = 30° in 1.3 sec	ϕ_t = 30° in 2.0 sec

3.3.2.3.2 DIRECTIONAL CONTROL CHARACTERISTICS

REQUIREMENTS

3.3.2.3.2 Directional Control Characteristics. Directional stability and control characteristics shall enable the pilot to balance yawing moments and control yaw and sideslip as required by the flight phase. Sensitivity to directional controller inputs shall be sufficiently high so the statisfactory coordination can be accomplished without undue operator effort, yet sufficiently low that occasional improperly coordinated controller inputs will not seriously degrade the flying qualities.

DISCUSSION (Related MIL-F-8785B paragraph 3.3.5)

Use of directional control for individual tasks is discussed in 3.4.4. Depending on configuration, recovery devices, and mission requirements, it may or may not be necessary to provide separate directional control devices on the vehicle. Even where they are provided, automatic directional trim and coordination as a function of other control inputs or state variables is recommended wherever possible, rather than having the operator handle this chore.

3.3.2.4 OPERATOR INDUCED OSCILLATIONS

REQUIREMENT

3.3.2.4 Operator Induced Oscillations. There shall be no tendency for operator-induced oscillations, that is, sustained or uncontrollable oscillations resulting from the efforts of the operator to control the vehicle.

DISCUSSION (Related MIL-F-8786B paragraph 3.2.2.3 and 3.3.3)

This requirement applies to both longitudinal and lateral-directional control. It was decided to retain this qualitative requirement because there are many factors determining the susceptibility of a given vehicle to operator-induced oscillations. Some of the known factors are short-term dynamics, control system dynamics, feel system phasing, control force and motion gradients, and control system friction and lost motion. Although it is hoped that such oscillations can be prevented by the requirements in these areas, requirement 3.3.2.4 is intented to serve as a check list and establishes the responsibility for correction of these problems with the contractor.

3.3.3 STABILITY MARGINS

REQUIREMENTS

3.3.3 Stability Margins. For FCS using feedback systems, the stability defined by 3.3.3.1 shall be provided. Alternatively, when approved by the procuring activity, the stability defined by the contractor through the sensitivity analyses of 3.3.3.2 shall be provided. Where analysis is used to demonstrate compliance with these stability requirements, the effects of major system nonlinearities shall be included.

3.3.3.1 Gain and Phase Margins. Required gain and phase margins about nominal are defined in Table 14 for all aerodynamically closed loop FCS. With these gain or phase variations included, no residual oscillations shall exist with amplitudes greater than those allowed in 3.3.3.3. AFCS loops shall be stable with these gain or phase variations for any amplitudes greater than those allowed in 3.3.3.3. In multiple loop systems, variations shall be made with all gain and phase values in the feedback paths held at nominal values except for the path under investigation. A path is defined to include those elements connecting a sensor to a force or moment producer. For both aerodynamic and nonaerodynamic closed loops, at least 6 db gain margin shall exist at zero airspeed. At the end of system wear tests, at least 4.5 db gain margin shall exist for all loops at zero airspeed. The margins defined by Table 14 shall be maintained under flight conditions of most adverse center-of-gravity, mass distribution, and external store configuration throughout the operational envelope and during ground operations.

TABLE 14. GAIN AND PHASE MARGIN REQUIREMENTS (db, DEGREES)

Mode / Airspeed / Frequency Hz	Below $V_{o\,MIN}$	V_{oMIN} To V_{oMAX}	At Limit Airspeed (V_L)	At 1.15 V_L
$f_M < 0.06$	GM = 6 dB (No Phase Requirement Below V_{oMIN})	GM = ± 4.5 PM = ± 30	GM = ± 3.0 PM = ± 20	GM = 0 PM = 0 (Stable at Nominal Phase and Gain)
$0.06 \le f_M <$ First Aero-Elastic Mode		GM = ± 6.0 PM = ± 45	GM = ± 4.5 PM = ± 30	
$f_M >$ First Aero-Elastic Mode		GM = ± 8.0 PM = ± 60	GM = ± 6.0 PM = ± 45	

where: V_L = Limit Airspeed

V_{oMIN} = Minimum Operational Airspeed

V_{oMAX} = Maximum Operational Airspeed

Mode = A characteristic aeroelastic response of the aircraft as described by an aeroelastic characteristic root of the coupled aircraft/FCS dynamic equation-of-motion.

GM=Gain Margin = The minimum change in loop gain, at nominal phase, which results in an instability beyond that allowed as a residual oscillation.

PM=Phase Margin = The minimum change in phase at nominal loop gain which results in an instability

f_M = Mode frequency in Hz (FCS engaged).

Nominal Phase and Gain = The contractor's best estimate or measurement of FCS and aircraft phase and gain characteristics available at the time of requirement verification.

3.3.3.2 Sensitivity Analysis. Tolerances on feedback gain and phase shall be established at the system level based on the anticipated range of gain and phase errors which will exist between nominal test values or predictions and in-service operation due to such factors as poorly defined nonlinear and higher order dynamics, anticipated manufacturing tolerances, aging, wear, maintenance and noncritical material failures. Gain and phase margins shall be defined, based on these tolerances, which will assure satisfactory operation. These gain and phase tolerances shall be established based on variations in system characteristics either anticipated or allowed by component or subsystem specification. The contractor shall establish, with the approval of the procuring agency, the range of variation to be considered based on a selected probability of exceedance for each type of variation. The contractor shall select the exceedance probability based on the criticality of the flight control function being provided. The stability requirements established through this Sensitivity Analysis shall not be less than 50 percent of the magnitude and phase requirements of 3.3.3.1, unless agreed upon by the procuring activity.

DISCUSSION

Requirements 3.3.3.1 and 3.3.3.2 are taken from MIL-F-9490D and are intended

to offer two approaches for establishing stability; respectively, they are:

(1) specific gain and phase margin requirements (Table 14)

(2) establishing gain and phase margin requirements of the actual system based on anticipated ranges of values tolerances, errors, etc.

The latter (3.3.3.2) will undoubtedly be more useful for RPV's. However, many RPV configurations will operate in a manner similar to present aircraft. For these more conventional configurations a more specific set of requirements could be applied (3.3.3.1).

The gain and phase margins specified in Table 14 are in the range of values used in previous successful procurements of aircraft and are considered minimums which will provide largely trouble-free service. The stability margins vary with frequency and airspeed. The reduction in margin at V_L reflects a willingness to accept reduced stability and/or performance outside the operational envelope. The increased margins at higher frequencies reflect caution based on the decreasing accuracy of state-of-the-art modeling and testing at the higher frequencies.

Although the philosophy above still applies, the values and frequency ranges referenced in Table 14 will undoubtedly need revision. Aside from standard control system design techniques, a more detailed study needs to be made of present RPV design practices and experiences to establish a new data base for specifying realistic requirements.

The remaining discussion was extracted from the background document MIL-F-9490D.

The gain and phase margin definitions listed are commonly used within flight control technology, and are not the classical definitions found in most textbooks. These margins are both positive and negative. A negative gain variation (reduction) can lead to instability on a basically unstable airframe which relies on the feedback system for dynamic stability. Positive and negative phase margins denote the amount of lag and lead that may be added, respectively, before instability occurs.

The margins specified vary with frequency. These margins can be determined using classical linear analysis techniques, adjusted for known nonlinearities. Normally in test a lower-frequency mode will set the test margins, and gain margins at higher frequencies will be unobservable. Consequently, compliance with these gain and phase margin requirements will likely be demonstrated through analysis in most procurements.

Figure 15 illustrates a typical FCS block diagram. Several feedback loops are shown; however, only one feedback path is shown, since only one sensor and one moment producer are involved. Thus, only one control path exists and only one stability requirement applies.

Stability margins are required for FCS to allow for variations in system dynamics. Three basic types of variations exist:

- o Math modeling and data errors in defining the nominal system and plant.

- o Variations in dynamic characteristics caused by changes in environmental conditions, manufacturing tolerances, aging, wear, noncritical material failures, and off-nominal power supplies.

- o Maintenance-induced errors in calibration, installation and adjustment.

Most low-frequency math modeling errors can be adjusted out during ground or flight tests to obtain the desired nominal operating characteristics. At high frequencies, math modeling errors are difficult to identify and compensate for during testing because of the approximations used to implement operational mockups, the limited amount of flight test time available and/or the limitations of instrumentation commonly used. In addition to the variations caused by the factors listed above, variations may result from usage of an inadequate number of flight conditions for a given analysis of a flight test program. Within the industry, flight control synthesis is normally accomplished using equations of motion defining aircraft and system characteristics at selected points on the flight envelope in various aircraft configurations. Flight testing is also normally concentrated at a limited number of points within the flight envelope. Selection of the number of type of flight conditions to be used is an individual decision in each procurement.

Another source of variations occurs following completion of the aircraft development. Following initial usage, most aircraft experience a series of minor modifications to improve operating characteristics. The modifications, which typically result in quite minor configuration changes on an individual basis, can result in significant changes in flight control stability margins as modifications are accumulated through several years. The original flight control system design should allow for such variations, such that FCS modification is not needed following a reasonable number of modifications.

The intent of including effects of major nonlinearities in analyses used to demonstrate compliance is to insure that adequate margins are retained with the systems operating both in the linear and nonlinear range. Most FCS exhibit rate limiting nonlinearities with large control surface amplitudes at higher frequencies. Deadband or hysteresis is also usually present. Data link characteristics (delays) should also be considered where applicable

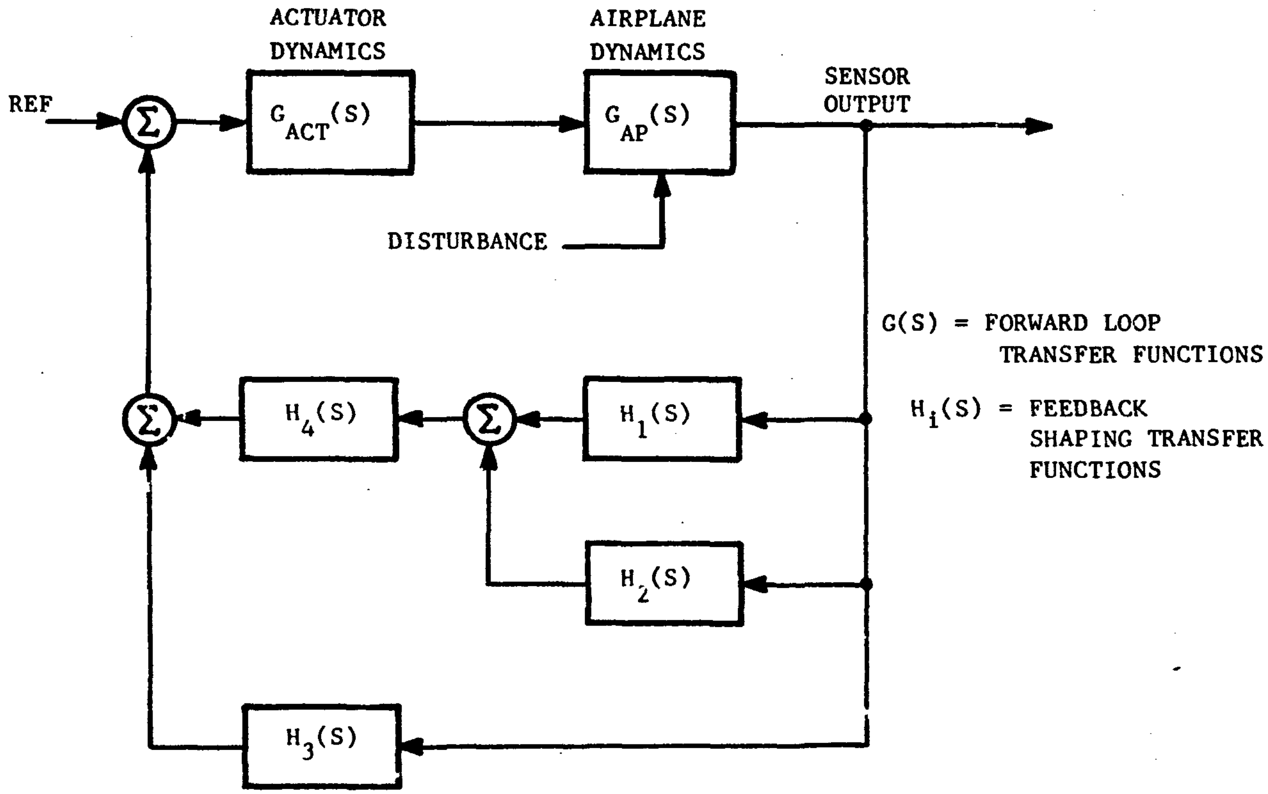


Figure 15. Typical FCS Block Diagram

(Section 3.5). Where linear analysis techniques such as root locus are used, phase and gain characteristics for the feedback elements operating at small perturbations should be considered to evaluate nonlinearities such as breakout deadzones or hysteresis, and, separately, phase and gain characteristics for feedback elements operating at medium and large control surface amplitudes should be considered to evaluate the near linear case and the rate limiting case. Where simulation is used, these nonlinearities can be included directly and evaluated by measuring frequency responses at different control surface amplitudes. The contractor may choose to use both linear analyses and nonlinear simulation techniques to demonstrate compliance with these requirements, since the linear analysis approach normally provides a better representation of aeroelastic effects and the simulation approach normally is superior for nonlinear evaluations.

The math models to be used for these stability analyses will vary with each procurement. The contractor will determine what math model complexity is required for each procurement and should include this model description in the FCS Development Plan.

3.3.3.3 RESIDUAL OSCILLATIONS

REQUIREMENTS

3.3.3.3 Residual Oscillations. Any sustained FCS residual oscillations shall not interfere with mission flight phase performance requirements or the operator's ability to perform the mission flight phase tasks required. Pitch, roll and yaw attitudes shall not exceed 0.6 degrees peak to peak for flight phases requiring precision control of attitudes.

DISCUSSION

This requirement applies to flight control systems which support both manual and automatic control. The purpose of the requirement is to prevent limit cycles in the control system which might compromise tactical effectiveness, or interfere with the operator's ability to perform flight phase tasks. The 0.6 degree peak to peak value is the same as stated in MIL-F-9490 for precision control in roll and yaw. The requirement states the same limit for pitch attitude which is a slight increase over the ± 3 mils given in MIL-F-8785B. For RPV's the main consideration is that the oscillations do not compromise mission effectiveness. Pilot discomfort is not a factor. The value stated in this requirement will be used unless otherwise specified by the procuring activity or mission flight phase requirements of 3.2. It is expected that the residual oscillation requirement will be strongly dependent on the mission or equipment requirements.

3.3.4 SYSTEM OPERATION AND INTERFACE

REQUIREMENTS

3.3.4 System Operation and Interface. Wherever a noncritical control or any other vehicle subsystem is interfaced with essential or flight phase control functions, sufficient isolation shall be provided to make the probability of propagated or common mode failures extremely remote. In any case, these reliability interfaces will be included when meeting the reliability requirements of 3.1.9.2.1 thru 3.1.9.2.3. A control function is essential if loss of the function results in loss of vehicle or flying qualities worse than Level 3. A Flight Phase function is essential if loss of the function would result in loss of vehicle or flying qualities worse than Level 3 only during specific flight phases.

3.3.4.1 Normal Engagement/Disengagement. When intentional manual or automatic control switching is initiated from one control mode to another the transients shall not interfere with the performance of the mission flight phase. No out of trim conditions shall exist during disengagement which cannot be easily controlled by the AFCS or operator.

3.3.4.1.1 Manual Override Capability. If direct manual override capability of an automatic flight control mode is to be provided, the combination of the manual override inputs and AFCS operation shall be compatible and not result in uncontrollable flight conditions or instabilities.

3.3.4.2 Automatic Engagement/Disengagement. When alternate modes are to be provided for FCS failure, failure detection logic will be provided to automatically select and engage these modes, and inform the operator of the AFCS mode selection. The operator shall be provided with the capability of manual mode selections when he is directly responsible for flying the RPV (primary or backup). This requirement will meet the conditions of 3.3.4.5.

3.3.4.3 Failure Transients. When automatic or manual backup modes are to be used to cover a FCS failure the time delay between failure and corrective action shall not result in flight conditions which will prevent recovery of vehicle control.

3.3.4.4 Flight Control Reliability. Unless otherwise specified, the contractor shall determine the need for redundancy based on the reliability requirements of 3.1.9.2.3.

3.3.4.5 Mode Selection Compatibility and Logic. When a choice of FCS mode is available, a mode hierarchy will be specified and the mode selection logic shall be capable of handling all possible combinations of desirable and inadvertent selections. The mode selection logic shall:

- Prevent the automatic or manual engagement of incompatible control modes which can create an immediate undesirable

vehicle situation.

- Provide the capability for use of appropriate modes which are consistent with the selection of certain modes.
- Provide for automatic engagement of the next lower operational FCS mode in the event of a failure of a higher-priority mode.
- Prevent operator from directly selecting a mode in which a failure has been detected, but may give the operator reset capability to allow for transient failures or find which mode is still good.

DISCUSSION

The intent of the above requirements is to insure adequate attention has been given to the needs and requirements of interfacing various flight control modes and systems. The above requirements are essentially taken from MIL-F-9490D.

3.3.4.6 SATURATION OF AUGMENTATION SYSTEMS

REQUIREMENT

3.3.4.6 Saturation of Augmentation Systems. Limits on the authority of augmentation systems or saturation of equipment shall not result in objectionable flying qualities. In particular, this requirement shall be met during rapid large-amplitude maneuvers, during operation near V_s, and during flight in the atmospheric disturbances of 3.3.5.

DISCUSSION (Related MIL-F-8785B Requirement 3.5.4.2)

This requirement has been introduced as a reminder to the designer that limiting the authority of augmentation devices for safety purposes also may limit the effectiveness for improving flying qualities. For instance, a limited-authority pitch-rate damper may improve ζ_{sp} in light turbulence for precision tracking tasks, but the nonlinearity of the vehicle's response for a pullup due to saturation of the rate damper might be extremely objectionable.

Some requirements of this document specify a minimum control power (for takeoff, landing, maneuvering flight, roll control, etc.) or a minimum control margin (for sideslip, cross-wind landing, asymmetric thrust, etc.) available to the pilot. Saturation of augmentation must not prevent the safe utilization of that control power or margin for maneuvering and compensating for disturbances.

3.3.4.7 SENSORS

REQUIREMENT

3.3.4.7 Sensors. Sensors shall be installed in locations which allow adequate sensing of the desired aircraft and flight control system parameters, and which minimize exposure to conditions which could produce failures or undesired output signals.

DISCUSSION

Careful attention must be given to the location and detail installation of all sensors to ensure that they provide signals of the quality necessary for the flight control system without distortion due to undesirable structural modes or other effects. The locations must not be such as to subject the sensors to damage or change of output characteristics due to operational and environmental conditions, and must be accessible for inspection, removal and reinstallation by maintenance personnel. Redundant air data sensors, for example, can cause problems because of natural variations in local flow fields.

3.3.5 ATMOSPHERIC DISTURBANCES

REQUIREMENT

3.3.5 Atmospheric Disturbances. Models for the evaluation of atmospheric disturbances such as discrete gusts, wind shear, and turbulence shall be chosen by the contractor subject to the approval of the procuring activity. Compliance shall be demonstrated by suitable analysis, test, or both, as determined by the procuring activity.

DISCUSSION

There are presently several forms of wind models used to evaluate aircraft requirements. Some are presented in terms of steady wind speed, others refer to discrete gusts, wind shear, and turbulence models (MIL-F-9490, MIL-F-8785B). In some cases, wind models for specific flight phases are specified, such as takeoff and landing. Sections 3.3.5.1 and 3.3.5.2 discuss wind and rain models for RPV vehicles, respectively. However, it remains for future efforts to review and evaluate present models for RPV application and to incorporate specific criteria under this requirement.

3.3.5.1 WIND/TURBULENCE/GUST MODELS

REQUIREMENTS

3.3.5.1 Wind/Turbulence/Gust Models. The wind models (to be established) shall be used to demonstrate satisfactory operation of the RPV flight control system. In particular, all or any part of the model will be applied to RPV design and analysis, as required by the procuring activity.

DISCUSSION

An effort is currently underway to revise the flying qualities specification for piloted aircraft (Reference 11) which includes revisions to the atmospheric disturbance models presently given in MIL-F-8785B. Discussions and revisions concerning the atmospheric disturbance model have been extracted from Reference 11 and are presented in Appendix A. Although the discussion is oriented toward piloted aircraft the actual disturbance model is more general and could be used as a basis for establishing future RPV wind disturbance model requirements for Section 3.3.5.1.

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3.3.5.2 RAIN MODEL

DISCUSSION

The following rain model recommendations were extracted directly from Reference 7.

Microwave frequency energy attenuation is caused by water absorption and is directly related to rainfall rate, raindrop size, radio frequency used, as well as other factors. Since the RPV landing system must operate satisfactorily in any of the selected climatic regions (Alaska, U.S., Central Europe, Middle East, SEA). The measured point rate rainfall during heavy rain in Southeast Asia was selected as the basis for the RPV recommended precipitation model presented in Table 15. This rain model is recommended for worldwide applications and will provide 99% weather reliability in the tropical areas and greater reliability in other areas. It is further recommended that this model be used for altitude to ten thousand feet since there is little variation over this altitude range. This model does not apply above ten thousand feet, because heavier rain rates are possible at the higher altitudes.

This model was empirically developed by the Environmental Technical Applications Center. The selected model has been previously used to estimate the rainfall encountered during manned aircraft approaches and has general acceptance. This model describes a rain storm consisting of several cells, the rainfall in each being proportional to a ten minute point rainfall.

In Table 15, rain models used in the design of other landing systems as well as measured worldwide worst cases are presented for comparison. For this data, it is seen that the recommended model for RPV automatic landing operations is consistent with the model selected for other landing systems and the assumption that, for RPV operations, site selection may be employed to minimize weather risks.

TABLE 15. COMPARISON OF RAIN MODELS

Rain Model	Rain Rate, mm/hr.				
	Heaviest Mile	Next 3 Mi	First 10 Mi Average	10-20 Mi Average	0-20 Mi Average
ETAC General Model	1.72R*	0.76R	0.72R	0.53R	0.62R
RPV Model	82.6	36.5	34.6	25.4	29.7
RTCA's SC-117 Landing System Model					
1% worst U.S.	19.8	6.86	7.11		5.08
0.1% worst U.S.	104.6	46.2	40.5		29.9
1% worst worldwide	49.3	20.8	20.0		17.4
0.1% worst worldwide	166.1	73.4	69.1		60.4
AN/TPN-19 Instrument Landing System Model	50	50	50		
Worldwide Extreme Rainfall - Point Rate	1872				

* R = measured ten minute point rainfall in the locale under consideration

3.4 VEHICLE REQUIREMENTS

GENERAL DISCUSSION

This section deals with the flying qualities of the air vehicle (See Figure 2), which includes onboard stability and control augmentation when it is provided.

Guidance and navigation are not considered part of this function, although they may be performed by onboard guidance and navigation equipment. Criteria for these functions have been defined at the mission and system level in Sections 3.2 and 3.3 respectively.

The purpose of the requirements of this section is to insure that the vehicle has sufficient control capability to meet and not limit the mission and system requirements of 3.2 and 3.3. An additional consideration of these requirements is to insure that the vehicle has residual stability and control characteristics which are sufficient to minimize dangerous flight conditions during momentary loss of the data link (specified in 3.5.3.2). The latter involves consideration of the value of the vehicle, the importance of the vehicle, etc., in determining the extent of onboard backup modes.

It is recognized that this is somewhat outside the concept of Level 3 requirements as described in Section 1.5, since the loss of data link to a vehicle under ground control will invariably be catastrophic if it continued too long. On the other hand, the intent is to provide for an occurance which can have a high level of probability for a given flight. In addition confusion may also result since the system requirements of Section 3.3, particularly the Manual Control section (3.3.2), will also contain Level 3 stability and control requirements. As defined in Section 1.5, Level 3M specifies the minimum characteristics which the operator requires to return and recover the vehicle following a failure at the most adverse point in the mission. Level 3A for automatic control has the same connotation, that is the degraded flying qualities of the automatic system is adequate to return and recover the vehicle. The implied Level 3 type vehicle requirement for momentary loss of data link is somewhat different. The intent is to consider onboard vehicle stability and control requirements which minimize the occurence of dangerous flight conditions during momentary data link dropout, and thus insure successful flight recovery of the vehicle following reacquisition of the data link.

Several possibilities to avoid confusion are:

1. Define a new Level 4

2. Define an additional Level 3 Category; e.g. Level 3V which deals with minimum vehicle requirements associated with data link transmission dropouts

3. Specify clearly within the specification that Level 3 system requirements in Section 3.3 are to exclude data

link failures, but Level 3 in the vehicle requirements is to include data link transmission failures

Of these three approaches the use of a new Level 3V seems most compatible at this time. It clearly identifies the requirement and reminds the user of the intent of the requirement. Since Level 3V will establish minimum requirements for the air vehicle such requirements will be stated under Vehicle Requirements (3.4). This approach in most respects is not much different than the use of the Vehicle Classification II-C or II-L in MIL-F-8785B where the letters - C and - L are used to specifically designate land based or carrier based aircraft.

In larger vehicles there is an increased likelihood of providing backup or dual systems. If this is the case, prudent design should allow for the failure of one of these, making the definition of Level 3V requirements necessary. There is no desire to require backup capability on all vehicles, but rather to provide design criteria when such a capability is specified. The procuring office will establish system backup requirements directly, or indirectly by specifying mission and vehicle reliability requirements in 3.2.

Depending on the mode of vehicle control, more stringent requirements may be imposed on the vehicle itself by Section 3.3; that is, the chosen control mode may place higher levels of requirements on the airframe and onboard augmentation and control system.

3.4.1 LONGITUDINAL CONTROL

GENERAL DISCUSSION

The requirements of the subparagraphs under 3.4.1 deal primarily with ensuring that the vehicle has adequate control effectiveness to fulfill its mission requirements. As a minimum, the control effectiveness must be adequate to attain any speed and altitude within the permissible envelope, and to attain required load factors (defined in 3.1). The control effectiveness must also be adequate to perform certain specific maneuvers associated with takeoffs, landings, dives, and sideslips.

These requirements have been taken mostly from MIL-F-8785B, and seem reasonable with little change.

3.4.1.1 LONGITUDINAL CONTROL IN UNACCELERATED FLIGHT

REQUIREMENT

3.4.1.1 Longitudinal Control in Unaccelerated Flight. In unaccelerated flight at all service altitudes, the attainment of all speeds between V_S and V_{max} shall not be limited by the effectiveness of the longitudinal control, or controls.

DISCUSSION (Related MIL-F-8785B paragraph 3.2.3.1)

This requirement simply states: the designer is required to provide enough control power to be able to trim throughout the service envelope.

3.4.1.2 LONGITUDINAL CONTROL IN MANEUVERING FLIGHT

REQUIREMENT

3.4.1.2 Longitudinal Control in Maneuvering Flight. Within the Operational Flight Envelope, it shall be possible to develop, by use of the longitudinal control and/or direct lift controls, the following range of load factors:

Levels 1 and 2 --- n_o (-) to n_o (+)

Level 3 ---------- n = 0.5 to the lower of:

a) n_o (+)

b) n = 2.0

This maneuvering capability is required at the 1g trim speed and, with trim and throttle settings unchanged, over a range about the trim speed the lesser of ±15 percent or ±50 knots equivalent airspeed (except where limited by the boundaries of the Operational Flight Envelope). Within the Service and Permissible Flight Envelopes, the dive-recovery requirements of 3.4.1.4 shall be met.

DISCUSSION (Related MIL-F-8785B paragraph 3.2.3.2)

Compared to 3.2.3.2 of MIL-F-8785B, this requirement is restricted in application to the Operational Flight Envelope with relaxed requirements for infrequent Failure States. Outside the Cperational Flight Envelope, whatever results from the design is acceptable, as long as the dive recovery control requirements are met.

The requirements for control effectiveness over a ±15 percent range about the trim speed assure for any possible mechanization of the trim system, that excessive amounts of elevator-surface-fixed static stability or instability will not unduly limit maneuver capability. Where elevator control authority limits normal-acceleration capability, the requirement at off-trim speeds often will be the designing consideration for elevator control effectiveness.

3.4.1.3 LONGITUDINAL CONTROL IN TAKEOFF

REQUIREMENTS

3.4.1.3 Longitudinal Control in Takeoff. The effectiveness of the longitudinal control shall not restrict the takeoff performance of the vehicle and shall be sufficient to prevent over-rotation to undesirable attitudes during takeoffs. Satisfactory takeoffs shall not be dependent upon use of the trimmer control during takeoff or on complicated control manipulation by the operator. For nose-wheel vehicles it shall be possible to obtain, at 0.9 V_{min}, the pitch attitude which will result in takeoff at V_{min}. For tail-wheel vehicles, it shall be possible to maintain any pitch attitude up to that for a level thrust-line at 0.5 V_S for Class I vehicles and at V_S for Class II, III, and IV vehicles. These requirements shall be met on hard-surfaced runways. In the event that a vehicle has a mission requirement for operation from unprepared fields, these requirements shall be met on such fields.

With the trim setting optional but fixed, during all manual controlled takeoffs for which the RPV is designed, including short-field takeoffs and assisted takeoffs such as catapult or rocket-augmented, longitudinal control travel shall not exceed 75 percent of the total travel, stop-to-stop. For purposes of this requirement, the term takeoff includes the ground run, rotation and lift-off, the ensuing acceleration to V_{max} (TO), and the transient caused by assist cessation.

On vehicles designed for catapult takeoff, the effectiveness of the elevator control shall be sufficient to prevent the vehicle from pitching up or down to undesirable attitudes in catapult takeoffs at speeds ranging from the minimum safe launching speed to a launching speed 30 percent or 30 knots higher than the minimum, whichever is less. Satisfactory catapult takeoffs shall not depend upon complicated control manipulation by the controller.

DISCUSSION (Related MIL-F-8785B paragraphs 3.2.3.3, 3.2.3.3.1, 3.2.3.3.2)

The requirement covers acceleration to V_{max} (TO) while allowing gear and flaps to be retracted normally. V_{max} (TO) is related specifically to the configuration in the takeoff flight phase, though the vehicle may no longer be in that configuration when V_{max} (TO) is reached.

Automatic takeoff systems sometimes utilize full control travel; however, a control travel requirement has been included for manual controlled takeoffs performed by the operator. The intent is to allow for the possibility of inexact operator performance and to allow for control authority for corrective action. It is not intended to penalize a vehicle in the event that a possible technique requires large control travel, if another easily learned and repeatable technique can be found that involves satisfactory control travel, at no sacrifice in performance. Any technique having all these latter qualities is acceptable.

3.4.1.4 LONGITUDINAL CONTROL IN DIVES

REQUIREMENT

3.4.1.4 Longitudinal Control in Dives. With the RPV trimmed for level flight at speeds throughout the Operational Flight Envelope, it shall be possible to recover from dives to all attainable speeds.

In lieu of this, clear and unambiguous warning of the approach to a dangerous condition must be given to the operator; or, automatic on-board limitation of the approach to a dangerous condition may be used so long as it does not interfere with the normal utilization of the RPV throughout the Operational Flight Envelope.

DISCUSSION (Related MIL-F-8785B paragraphs 3.2.3.5, 3.2.3.6)

The intent of this requirement is the same as that of paragraphs 3.2.3.5 and 3.2.3.6 of MIL-F-8785B, with modifications to reflect operator control. An automatic mode should prevent the approach to an overspeed condition as part of its normal design, but a manual mode would not normally have this safeguard. On-board provisions for avoiding this condition are preferable, either in the form of inherent airframe thrust/drag relationships or velocity limiting, but a vehicle of the RPRV type which is likely to be more closely monitored at all times may utilize the pilot warning technique.

3.4.1.5 LONGITUDINAL CONTROL IN LANDING

REQUIREMENT

3.4.1.5 Longitudinal Control in Landing. The longitudinal control shall be sufficiently effective in the landing Flight Phase in close proximity to the ground, that:

a) the geometry-limited touchdown attitude can be maintained in level flight, or

b) the lower of V_S (L) or the guaranteed landing speed can be obtained.

This requirement shall be met with the vehicle trimmed for the Approach Flight Phase at the recommended approach speed. The requirements define Levels 1 and 2. For Level 3, it shall be possible to execute safe approaches and landings in the presence of atmospheric disturbances specified by the procuring activity.

DISCUSSION (Related MIL-F-8785B paragraph 3.2.3.4)

Some manufacturers consider the requirements to fly near the ground at V_{S_L} unnecessarily strict. However, the requirement is necessary because of the imprecise nature of the landing flare maneuver. It is quite probable for an operator, intentionally or unintentionally, to hold the airplane off the ground during the landing flare until the speed is well below the normal landing speed. In this event, it is essential that the operator have enough longitudinal control to prevent the nose wheel from hitting the runway before the main gear. V_S(L) is defined as being determined out of ground effect.

An additional requirement seems to be needed to assure that vehicles with large pitching inertia will have adequate landing flare capability. A neutrally stable vehicle, or one with thrust below the c.g. or with pitch-up, could meet these requirements and still not have enough control. Some minimum pitching acceleration capability is needed in approaches at speeds down to V_{min}. However, there was not enough information to allow a definitive general requirement to be written.

3.4.1.6 LONGITUDINAL CONTROL IN SIDESLIPS

REQUIREMENT

3.4.1.6 Longitudinal Control in Sideslips. With the vehicle trimmed for straight, level flight with zero sideslip, the longitudinal control required to maintain constant speed in steady sideslips with up to 50% of directional control in either direction shall not exceed the longitudinal control deflection that would result in a 1g change in normal acceleration.

If a variation of longitudinal control with sideslip does exist, it is preferred that increasing nose-up control accompany increasing sideslip, and that the magnitude and direction of the control change be similar for right and left sideslips.

DISCUSSION (Related MIL-F-8785B paragraph 3.2.3.7)

There are two primary reasons for having requirements for maximum longitudinal control inputs in sideslips. The first is to ensure that small amounts of sideslip inadvertently developed during normal operations do not result in large or possibly dangerous angle-of-attack changes. The second reason is simply to limit the longitudinal corrections required when the pilot intentionally changes the sideslip angle, as in a crosswind landing.

It is not the intention of this paragraph to require a directional control device, but rather to ensure control harmony if one is provided.

Negative pitching moments in sideslips are conducive to stall/spin avoidance and recovery.

3.4.2 ROLL CONTROL
3.4.2.1 DIHEDRAL EFFECT
3.4.2.1.1 POSITIVE EFFECTIVE DIHEDRAL LIMIT

REQUIREMENT

3.4.2 Roll Control. Sufficient roll control effectiveness shall be provided to meet the maneuvering requirements of 3.3 in either direction from trim positions for the worst asymmetric loadings in each flight phase. The variation of bank angle with time following an abrupt lateral control device deflection shall always be in the correct direction. At any speed, the maximum rolling velocity obtained by abrupt deflection of the lateral control device shall be approximately proportional to controller deflection from the trim position. The roll control shall be sufficiently effective to balance the vehicle in roll throughout the Service Flight Envelope in the atmospheric disturbances of 3.3.5.

3.4.2.1 Dihedral Effect. The vehicle shall exhibit positive dihedral effect as indicated by the control deflection and control force toward the leading wing required to depress the leading wing in order to maintain a steady angle of sideslip. The rolling moment due to sideslip shall never be so great that a reversal of rolling velocity occurs during lateral control inputs. The variation of total side force with angle of sideslip shall be such that right skidding turns accompany right directional control deflection and vice versa when the wings are held level.

3.4.2.1.1 Positive Effective Dihedral Limit. For levels 1 and 2, positive effective dihedral (right control for right sideslip and left lateral control for left sideslip) shall never be so great that more than 75 percent of roll control power is required for sideslip angles which might be experienced in service employment.

DISCUSSION (Related MIL-F-8785B paragraphs 3.3.6 and 3.3.6.3.2)

The intent of 3.4.2 is to insure adequate vehicle roll control effectiveness throughout the flight envelope.

As written, requirement 3.4.2.1 accurately defines dihedral effect for vehicles with both roll and yaw controls. The purpose is to insure lateral stability, that is, a spiral mode that is not too rapidly divergent (see 3.4.5.3) and that the vehicle will tend to return to wings level or trim condition following a disturbance in bank. It is not intended to require either aileron or rudder control devices specifically. An on-board aileron/rudder interconnect would be acceptable to meet the aileron roll requirements.

Requirement 3.4.2.1.1 specifies allowable control power necessary for sideslips. Since this requirement relates directly to RPV usage, that is, the size of sideslip which "might be experienced in service employment," and

since this is a very strong function of RPV type, the requirement is tied to normal operational usage as was the corresponding requirement in MIL-F-8785B. A margin of control power must be left to cope with disturbances.

As defined in 3.3.2.3.1 control power is expressed in terms of moment-producing capability. There generally is a known or measurable relationship between surface deflection and control moment. The margin stated must be available for effective control, over and above any surface deflection used for stability augmentation. As noted in 3.3.4.6, the saturation of augmentation will not be allowed to prohibit safe use of this control margin for maneuvering and compensating for disturbances.

3.4.3 DIRECTIONAL CONTROL

REQUIREMENT

3.4.3 Directional control. Yaw control shall be sufficiently effective to balance the vehicle directionally as required in 3.3. There shall be no objectionable nonlinearities in the variation of directional response with control deflection.

DISCUSSION (Related MIL-F-8785B paragraph 3.3.5 and 3.3.5.1.1)

The intent is adequate directional control effectiveness.

3.4.4 LATERAL - DIRECTIONAL SIDESLIP CONTROL

GENERAL DISCUSSION

One of the more difficult problems in this section is how best to specify the flying quality characteristics involving sideslips. Sideslips can be either steady or dynamic and can develop in many ways. They can be caused by control inputs and coupling effects, by thrust or aerodynamic asymmetries such as engines out, asymmetric store loadings, and uneven gear retraction or extension, or by atmospheric disturbances. Since the implication of sideslip to flying qualities depends upon the nature of the forcing function and the type of maneuvers to be performed, it is necessary to specify several different requirements to cover the most significant combinations of forcing functions and required maneuvers.

Directional controls are used for many different purposes. Although no list of directional control usage would be complete, some of the more important uses are listed below.

a. To perform a crosswind landing - either employ a steady rudder-induced sideslip or else a decrab maneuver.

b. To augment roll rate anywhere within the flight envelope.

c. To raise a wing, or to provide primary roll control.

d. For tracking, for example, in air-to-ground gunnery in a crosswind or when acquiring targets.

e. For wing-overs or other tactical maneuvers to obtain a rapid change in heading or bank angle.

f. For close formation flying.

g. To counter yawing moments from propeller torque, speed or Mach number change, asymmetric thrust or stores, etc.

h. To coordinate turn entries or steady turns.

i. To taxi.

In order to avoid confusion, we will repeat the following conventions:

Right directional control is the control surface deflection that causes the vehicle to yaw nose right (starboard), placing the incident air flow on the left (portside) of the nose.

Positive, or right sideslip corresponds to incident
air flow approaching from the right (starboard) side.

Positive yaw rate (nose moving to starboard) corresponds
to that caused by right directional control and results
in negative sideslip.

3.4.4.1 STEADY SIDESLIP CHARACTERISTICS

REQUIREMENT

3.4.4.1 Steady Sideslip Characteristics. For directional control-induced steady, zero-yaw-rate sideslips with the aircraft trimmed for wings-level straight flight, right directional control deflection shall produce left sideslip and vice versa.

An increase in right bank angle shall accompany an increase in right sideslip and vice versa. Left lateral control deflection shall accompany left sideslips and vice versa.

DISCUSSION (Related MIL-F-8785B paragraphs 3.3.6.2, 3.3.6.3)

This requirement is important for two reasons: first, to ensure familar aircraft response characteristics for manual control modes; and second, to help ensure spiral stability.

Taking familar aircraft characteristics first, it has been demonstrated that cross-control is undesirable for several reasons, but principally because in tracking tasks operators prefer to have lateral control acting to damp Dutch roll oscillations while aiming is accomplished with directional control. Logically, this should be expected to carry over to RPV's where operators may be more tolerant of small amplitude oscillations because they are less aware of them, but performance will surely be degraded. This opens up a much larger subject which is beyond the scope of this paragraph, implying that the roll component of the Dutch roll oscillation is large enough for the operator to act to reduce it, and the phasing of the roll/sideslip oscillations such that lateral control inputs to damp the roll oscillation will generate yawing moments that damp rather than reinforce sideslip oscillations. An attempt was made in MIL-F-8785B to tie together some of these parameters, such as Posc/Pavg and $\measuredangle\, p/\beta$, but it has apparently turned out to be of limited use in design. As the present document is intended for just such a use, it was felt better to avoid this much detail until a direct input to the design process can be established.

In the case of vehicles without ailerons or other lateral controls to produce rolling moment directly, which is common practice in simple radio-controlled models, lateral stability (C_{ℓ_β}) must be high enough to provide the required rudder roll control without excessive sideslip.

An interrelationship with the spiral stability requirements of Section 3.4.5.3 is noted. Spiral stability is largely a function of the relationship between directional stability (C_{n_β}) and lateral stability (C_{ℓ_β}).

3.4.4.2 TAKEOFF AND LANDING ROLL IN CROSS WINDS

REQUIREMENTS

3.4.4.2 Takeoff And Landing Roll In Cross Winds. There takeoff and landing are applicable, the lateral control device(s) in conjunction with other means of roll control shall be adequate to maintain straight paths on the ground during normal takeoff and landing and in cross winds of a velocity up to 30% of $V_S(L)$ at 90 degrees to the path within a range of 10 knots minimum to 25 knots maximum.

If the procuring activity feels that these levels are too low for a certain system, taking into account the normal landing system, it will specify higher limits.

For level 3 operation, if applicable, the maximum cross wind velocity for demonstration shall be 10 knots.

DISCUSSION (Related MIL-F-8785B paragraphs 3.3.7.2)

MIL-F-8785B requirements have been lowered to 30 knots from 40 in the earlier version. Meteorological data indicated a 25 knot requirement would give 99.5 per cent operational effectiveness at present Air Force bases; the figure was upped to 30 to account for the difference between forecast and actual conditions at the time of landing, and slightly higher probabilities of exceeding the limit crosswind at a few individual overseas bases. Realistically, much of this caution is due to the presence of a pilot on present military aircraft, and the need for higher reliability. A relatively low cost RPV should not be penalized by allowing for such safety margins. In addition, a high fixed level becomes prohibitive in comparison with potential landing speeds of some smaller RPV's.

If the RPV system utilizes an unconventional mode of landing (parachute descent, net capture, etc) this requirement obviously doesn't apply.

3.4.4.3 FINAL APPROACH IN CROSS WINDS

REQUIREMENT

3.4.4.3 Final Approach In Cross Winds. For all RPV's except land-based RPV's equipped with cross-wind landing gear, or otherwise constructed to land in a large crabbed attitude, directional and lateral control power shall be adequate to develop the maximum sideslip angles given in Figure 16 for the minimum normal landing speed and maximum crosswinds specified by the procuring activity.

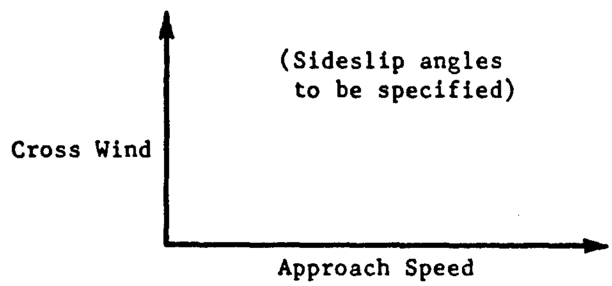

Figure 16. Final Approach Sideslip Requirements

DISCUSSION (Related MIL-F-8785B paragraph 3.3.7.1)

In aircraft operational experience, the 10 degrees of sideslip specified in MIL-F-8785B has often been needed as a bare minimum capability. Because of the possible ranges in airspeeds for RPV's the above requirement defines sideslip requirements as a direct function of cross wind and approach speeds to insure adequate sideslip capability.

The requirement of 3.4.3.2 may impose a more severe requirement, especially for vehicles dependent on rudder for control on the ground. Unconventional landing systems may invalidate the need for this requirement.

3.4.5 VEHICLE STABILITY

GENERAL DISCUSSION

Section 3.3 specified the equivalent system stability and control characteristics for the total RPV system. This included the combined operational characteristics of vehicle, data link, and control station. Those requirements do not distinguish between control loop augmentation which may be located on the ground (control station), on board the vehicle, or both. The intent of the vehicle stability requirements in this section (3.4.4) are to insure that the onboard air-vehicle flight control provides, as a minimum, sufficient vehicle stability and control to minimize dangerous and unrecoverable flight conditions during momentary dropout of the data link. These requirements include onboard vehicle stability augmentation when it is used.

These requirements actually will depend on the allowable dropout time specified in 3.5.3.2. However, the present requirements are expressed in terms of limiting divergence in the basic response characteristics of the vehicle (e.g., roll, spiral, short term, etc.). Future development of these requirements should consider defining such divergent limits as a function of data link dropout time.

As pointed out in the general discussion of 3.4 these types of requirements are somewhat different in concept from the Level 3 requirements as defined in Section 1.5. It is proposed that perhaps an additional Level '3V' be considered to designate minimum vehicle requirements. Further, although such requirements would be stated under Vehicle Requirements (3.4.4) it seems reasonable to also consider including some cross references between these requirements and related System Requirements (3.3). For example Level 3M spiral divergence of the total system (as presently stated) is 4 seconds (3.3.2.2.3). The minimum Level 3V vehicle stability requirement for data link dropout may not permit such a short divergence time and thus would impose a more stringent limitation. This is only a theoretical example since the values given in the requirements of this document reflect manned aircraft flying qualities and need to be evaluated and updated for RPV's.

3.4.5.1 DIRECTIONAL STABILITY

REQUIREMENT

3.4.5.1 Directional Stability. The vehicle shall posess static directional stability such that the vehicle will return to zero or the trim sideslip when controls are released for sideslip up to 15° at any load factor within the operational envelope.

If directional control is provided, it shall be demonstrated that right directional control deflection from the position for wings-level straight flight produces left steady sideslip, and vice versa. For angles of sideslip between plus and minus 15 degrees from the wings-level straight flight value, the change in angle of steady sideslip shall be substantially proportional to the directional control deflection from its wings-level straight flight setting. For sideslip increments greater than 15 degrees, increases in directional control deflection shall produce increases in the angle of steady sideslip up to full directional control deflection. For angles of sideslip between plus and minus 10 degrees, the angle of steady sideslip shall be substantially proportional to the directional control force for trim.

DISCUSSION (Related MIL-F-8785B paragraph 3.3.6.1)

This requirement has been updated from one of the predecessor documents to MIL-F-8785B, MIL-F-18150. In that document it was titled "static directional stability" and that is the context in which it is intended in this criteria. Although expressed in terms of control releases, it is not intended to imply that any particular types of controls are required.

3.4.5.2 ROLL MODE

REQUIREMENT

3.4.5.2 Roll Mode. The vehicle roll time constant, τ_R, shall not be less than 5 seconds following loss of data link command signals.

DISCUSSION

The roll damping has been expressed in terms of a first order roll time constant, τ_R.

3.4.5.3 SPIRAL STABILITY

REQUIREMENT

3.4.5.3 Spiral Stability. The vehicle spiral stability, including flight-control-system characteristics, and trim change with speed shall be such that following a disturbance in bank of up to 20 degrees, the time for the bank angle to double will be greater than 4 seconds. This requirement shall be met with the vehicle trimmed for wings-level, zero-yaw-rate flight.

DISCUSSION (Related MIL-F-8785B paragraph 3.3.1.3)

The requirement on spiral divergence is aimed primarily at ensuring that the vehicle will not diverge too rapidly from a wings-level condition during periods of pilot inattention or data link dropout.

This requirement as stated reflects MIL-F-8785B Level 3 requirements for spiral stability and is also used in 3.3.2.2.3 for the Level 3M spiral stability characteristic of the total system when manual control is used. Requirement 3.4.5.3 may not be stringent enough (See discussion under 3.4.4).

3.4.5.4 SHORT TERM STABILITY

REQUIREMENT

3.4.5.4 Short Term Stability. The vehicle short-term dynamic oscillation of normal acceleration produced by moving and quickly releasing the longitudinal control shall not exhibit a tendency to diverge faster than a time to double amplitude of 15 seconds, or to diverge so as to cause structural failure or to render any element of the vehicle incapable of functioning following loss of command signals for 15 seconds in the atmospheric conditions of 3.3.5.

DISCUSSION (Related MIL-F-8785B paragraphs 3.2.1.1, 3.2.2.1.2)

This is intended to prevent the loss or incapacity of the vehicle during momentary loss of the data link. The 15 second time to double amplitude number is somewhat random but was chosen to convey the feeling of the maximum instability that will be permitted. Normally, the level 3 system requirements of 3.3.2.1 will be the determining factor.

3.4.5.5 FLIGHT PATH STABILITY

REQUIREMENT

3.4.5.5 Flight Path Stability. No dangerous or unrecoverable conditions shall result from loss of command signal for a period of 15 seconds.

DISCUSSION

Such a requirement as the above needs to be carefully evaluated in more detail. This can depend on such factors as initial margin from stall, and altitude (flight phase). In fact this requirement might well determine these factors.

3.4.6 MISCELLANEOUS REQUIREMENTS
3.4.6.1 BUFFET

REQUIREMENT

3.4.6 Miscellaneous Requirements.

3.4.6.1 Buffet. Within the bounda·.es of the Operational Flight Envelope, there shall be no objectionable buffet which might detract from the effectiveness of the vehicle in executing its intended mission.

DISCUSSION (Related MIL-F-8785B paragraph 3.4.6)

Tolerance for buffet may be quantified for the RPV mission as a function of mission requirements as well as structural fatigue. For many missions, buffet may not be a problem (communications relay for e.ample), while video target acquisition and photographic missions may impose severe restrictions, but only for the particular phase during the mission when this equipment is active.

3.4.6.2 DEPARTURE FROM CONTROLLED FLIGHT
3.4.6.3 ASYMMETRIC POWER
3.4.6.4 STALLS
3.4.6.5 RECOVERY FROM SPIN AND POST-STALL GYRATIONS
3.4.6.6 TRIM DEVICES

REQUIREMENTS

3.4.6.2 Departure From Controlled Flight. All classes of vehicles shall be extremely resistant to departure from controlled flight, to post-stall gyrations, and to spins within the operational flight envelope. The vehicle shall exhibit no uncommanded motion which cannot be arrested by simple applications of operator or augmentation system control.

3.4.6.3 Asymmetric Power. Following sudden asymmetric loss of thrust, the vehicle shall be safely controllable to execute vehicle recovery or other contingency procedures, as specified. It shall be possible to maintain control of the vehicle on the takeoff surface following sudden asymmetric loss of thrust. During takeoff, it shall be possible to achieve straight flight following sudden asymmetric loss of thrust and to maintain straight flight throughout the climb-out.

3.4.6.4 Stalls.

3.4.6.4.1 Stall Approach. The stall approach shall be accompanied by an easily perceptible warning. The onset of this warning shall not occur within the Operational Flight Envelope. The warning shall continue until the angle of attack is reduced to a value less than that for warning onset. At all angles of attack up to the stall, the control inputs shall not result in departure from controlled flight. (Consideration should be given to specifying a stall margin of warning in this requirement).

3.4.6.4.2 Stall Characteristics. It is desired that no pitch-up tendencies occur in accelerated or unaccelerated stalls.

3.4.6.4.3 Stall Prevention And Recovery. It shall be possible to prevent the stall by moderate use of the longitudinal control alone at the onset of the stall warning. It shall be possible to recover from a stall by simple use of the controls and to regain level flight without excessive loss of altitude or buildup of speed.

3.4.6.4.4 Stall margin in turn. In steady turning flight and in pullups at constant speed within the Operational Flight Envelope associated with the Vehicle Normal State, the maximum percentage of lift shall not exceed 85 percent of $C_{L_{STALL}}$.

3.4.6.5 Recovery From Spin And Post-Stall Gyrations. If spin recovery is required, the proper recovery technique(s) must be readily ascertainable by

the operator. A single technique shall provide prompt recovery from all post-stall gyrations and incipient spins, without requiring the operator to determine the direction of motion and without tendency to develop a spin. The same technique used to recover from post-stall gyrations and incipient spins, or at least a compatible one, is also desired for spin recovery. Avoidance of a spin reversal or an adverse mode change shall not depend upon precise operator control timing or deflection. It is desired that all aircraft be readily recoverable from all attainable attitudes and motions.

3.4.6.6 Trim Devices. The trimming devices shall maintain a given setting indefinitely unless changed by command from the operator or the AFCS. Trim changes at any speed due to changing power, flap or gear setting, shall be made as small as possible to minimize transients. (This requirement should be expanded to include runaway trim.)

3.5 - 3.5.3 DATA LINK REQUIREMENTS

REQUIREMENTS

3.5 Data Link Requirements. When information is transmitted between control station and RPV via a digital data link, the sampling frequency and number of bits per signal shall be compatible with the accuracy and dynamic performance requirements of the system functions involved. If an analog data link is used, the gain variation and zero shift of the data link shall be compatible with performance and accuracy requirements of the system function.

The data link shall not cause degradation in total vehicle response, stability, or accuracy nor performance characteristics which are incompatible with the requirements of this specification.

3.5.1 Data Link Range. The data link shall provide the performance specified in 3.5 through 3.5.3 for the maximum operational mission range defined in 3.1.1 by the procuring agency.

3.5.2 RPV Maneuvers. Capability shall be incorporated on the RPV to insure data link operation for all vehicle attitudes and headings, which will be encountered throughout the combined regimes of mission flight plans and vehicle maneuvers.

3.5.3 Data Link Operation. The data link shall provide the specified communication, command and control signals required to accomplish the mission.

3.5.3.1 Transmission Reliability. The data link shall provide the jam resistent transmission characteristics specified for minimizing interrupted operation during the mission. Communication environments (random noise and/or threat environments) are to be specified by the procuring activity.

3.5.3.2 Loss or Dropout of Communication Link. Vehicle flight control modes and operational contingency procedures shall be established for loss of the communication link. If the link is not reacquired after ___ seconds, the operational contingency procedures shall be executed. During this time, the onboard air vehicle flight control modes shall provide, as a minimum, sufficient stability and control to minimize dangerous or unrecoverable flight conditions (3.4.5). Status displays shall inform remote operator when the data link dropout exceeds ___ seconds. (Times are to be determined.)

DISCUSSION

In general, the data link requirements will be detailed in a separate system specification. The intent of requirement 3.5 is to insure that data link characteristics, when applicable, are identified and considered in the design analysis of the automatic or manual flight control mechanization. The important parameters are:

- Sampling frequencies for guidance, control, or augmentation loops.

- Resolution accuracies

- Information update rates for operator monitoring and/or flight control.

- Jam resistance characteristics

The data link characteristics will vary depending on the RPV system, flight tasks to be performed, and the amount of signal interface required with ground equipment. The data link can consist of a narrow band uplink (command) and control, a narrow band downlink (position/status) and possibly a wide band downlink for transmitting video or imaging sensor information. The narrow band uplink will be used to transmit guidance/navigation, flight control steering, prime mission equipment and sensor commands. The downlink will provide status and performance information to the operator. However, in some cases, portions of the vehicle guidance, and augmentation loops may be located on the ground. In these cases, the combined downlink and uplink transmission rates and accuracies must be compatible with control loop and vehicle characteristics to insure that the vehicle response, stability and/or guidance are not degraded beyond the requirements of this specification, or other related requirements specified by the procuring agency.

The intent of requirement 3.5.3.2 is to ensure that reasonable flight control procedures and capabilities have been considered for the air vehicle in the event of loss of data link. Obviously, the allowable dropout time, and the contingency modes and procedures will depend on the type of vehicle, the mission flight phase being performed, the method of control at time of failure (automatic or manual), the degree of communication failure (command and control uplink, status downlink, and/or wideband video downlink), and the mechanization of the data link (omni or directional). This requirement further points out the need for minimum stability and control considerations onboard the vehicle to minimize the occurrence of unrecoverable flight conditions for intermittent data link dropouts, and during the time allowed (to be specified) for reacquisition.

3.6 CONTROL STATION REQUIREMENTS

REQUIREMENT

3.6 Control Station Requirements

DISCUSSION

This section contains four principal sub-sections: Human Factors, Operator Displays, Operator Controller Characteristics, and Specialized Flight Phase Displays and Controls. The first section applies to human factor guidelines for console, displays and controls design. The Operator Displays section deals with minimum display information requirements. The Operator Controller Characteristics section identifies the basic manual control force-motion and response requirements.

The intent of the final section is to provide for specialized display and control criteria as applied to the four principal operational phases of RPV operation. The general conclusions of the man-machine interface studies lead to the recommendation that an 'area control' approach be used, in which different operators using specialized displays and controls are responsible for separate launch, enroute and terminal strike or recovery mission flight phases. Based upon this rationale, it was decided that the requirements should provide for specialized display and control criteria relating to each of these specific areas. Obviously the requirements on remote displays, controls, and parameters displayed will vary depending on many factors related to:

- The intended complexity of the air-vehicle system and type of mission (simple Mini RPV operations versus complex multi-RPV operations involving multi-mission capability), and
- The man-machine functional allocations for the different mission flight phases.

However, presenting requirements in this manner should provide a more straight-forward identification of display and control requirements. Further, comparison of these requirements in terms of commonality and task difficulty will provide guidelines for combining display, control, and operator functions for simpler RPV air-vehicle systems.

3.6.1 HUMAN FACTORS

REQUIREMENT

3.6.1 Human Factors. The human factors considerations in the design and arrangement of the remote control station, consoles, displays, and controls will be in accordance with the principles set forth in MIL-STD-1472A entitled Human Design Criteria for Military Systems, and the supporting material of the Joint Services Human Engineering Guide to Equipment Design.

DISCUSSION

The above refers to the standard human engineering design criteria documents used by the military. As more detailed RPV flying quality requirements are established in the future there may be a need to specify particular human factor interface requirements. However, for the present the above two documents (References 12 and 13) are to be used.

Console and display design considerations and arrangements are also discussed in the Man-Machine Interface Studies and DCDRS Studies (References 14 thru 24.

The man and machine allocations should utilize the best capabilities of both: machines to provide high-speed, error-free computations, performance and data manipulation; and the man to provide judgemental and/or decision-type control. The degree of automatic control will obviously depend on the complexity and limitations of the specific air-vehicle system. Less sophisticated manual control capability along with reduced automation can be expected in the simpler Class I vehicles (mini RPV), where data link and ground control complexity would not be available.

3.6.2 OPERATOR DISPLAYS

3.6.2.1 STATUS DISPLAYS

REQUIREMENTS

3.6.2 Operator Displays

3.6.2.1 Status Displays. Displays shall be provided to monitor system and subsystem functions critical to vehicle operation and mission performance.

3.6.2.1.1 Failure Warnings and Status Annunciation. Failure warnings and critical status annunciations shall be provided to alert the operator. These annunciations shall clearly designate which system is involved and the associated degree of urgency:

- First degree: Immediate action required by operator
- Second degree: Caution, operator action may be required.
- Third degree: Informational or instructional status for monitoring or controlling vehicle. No immediate action required.

The first-degree warnings comprise failures which would result in mission failure or vehicle loss if immediate action were not taken, and shall be located within the normal eye scan range of the controller.

3.6.2.1.2 Flight Control Mode Annunciation. Flight control mode engagements and disengagements shall be clearly displayed to the operator. This includes manual engagements, automatic operator assist modes (e.g., attitude hold engaged), and any automatic mode switching that has occured. Failure warnings shall be displayed to allow operator(s) to assess status of redundant or monitored flight control system components.

3.6.2.1.3 Control Authority Annunciation. If manual control authority can be reduced below the level required for maneuver control by a function such as manual or automatic trim, or stability augumentation, displays shall indicate manual control available.

3.6.2.1.4 Vehicle Configuration Indicators. Displays shall be provided to inform operator of vehicle configuration and geometry characteristics essential for performance and mission flight phase accomplishment. This shall include landing gear, lift, thrust, and drag devices which have different control positions. Examples are: flaps and landing gear up or down, wing angle, thrust angle and speed brake deployment.

3.6.2.1.5 Trim Indicators. When used, suitable indicators shall be provided to indicate the range of travel of each trim device. The operator will be provided with trim failure warnings which could result in Level 3 flying qualities. See Trim Device Requirement (3.4.6.6).

DISCUSSION

The status displays provide information to:

- Detect and diagnose malfunctions or unsatisfactory system operation.
- Monitor real-time system performance.
- Provide preselected model parameters and input data formats which enable operator to enter data or update commands as rapidly as possible.

Three levels of status annunciation are recommended. Examples are given in Table 16. A further identification of the status levels is:

1. Immediate Action Required - loss of system function, hazardous vehicle condition imminent.
2. Caution, Action may be Required - Probable loss of system function. Hazardous vehicle condition may be developing or mission may not be accomplished. Operator should make an assessment of system status before responding.
3. Informational, No Immediate Action Required - possible loss of system function in near future. No impending hazard. An example is identification of a failure in pretest of a system. Hazard can be avoided by not using that system or mode.

TABLE 16. RECOMMENDED LEVELS FOR STATUS MONITORING

Status Level	Operator Alerting Examples	Status Examples
First Degree - Immediate operator action required.	Annunciation Lights (Red). Flashing imaging display or symbol. Audible signal.	• Loss of system function, hazardous condition imminent. • Guidance/navigation computer failure-guidance commands required. • Navigation errors unsatisfactory - navigation update required. • Communication outage.
Second Degree - Caution - operator action may be required	Same as above but distinguished by color (yellow) or rate of flashing.	• Loss of position updates (LORAN). Manual updates may be required • Prime mission equipment failure
Third Degree - Informational/instructional data.	Available by call up or automatically displayed. Divided into data grouping for quick operator assimilation. Alphanumeric display recommended for complex RPV systems which require a large amount of status information.	• Operator selects desired status display to monitor or diagnose failures, or to use data format entries.

The probability of losing the capability to isolate failures and annunciate system status should be minimized. This may require special considerations relative to power source selection. For example, if failures are annunciated by lights, then the design must ensure power to the lights when the channel failure is a power failure. Also, buffering should protect the annunciation circuits from electrical transients.

The probability of the operator mismanaging a safety-critical system should be minimized. Zealous pursuit of this objective can lead to criteria which require implementation of interlock logic that prevents the operator from isolating a critical channel unless the channel has been annunciated as failed, and which prevents the operator from re-engaging critical channels that have been isolated ude to a prior failure indication. The first and second status levels should use dedicated displays to alert the operator directly (such as annunciation lights, flashing, or audio-signals). The third status level, which is informational, should be readily assessable to enable the operator to evaluate system performance or failure effects as quickly as possible. When a large number of data items is involved, alpha-numeric video readout should be considered for ease of data assimulation. When the same parameter(s) are important for interpretation in two different data groupings, and sequential type displays are used, these common parameters should be included in both.

It is recommended that the basic information and instruction status displays be divided into data groupings to enable quick assessment by the operator. Possible groupings are: Guidance and Navigation Parameters, Vehicle Flight Control Parameters, and Prime Mission Equipment (PME). The Guidance and Navigation and Vehicle Flight Control information are discussed in more detail under Section 3.6.4. PME status should include results of status checks and state of readiness of mission equipment.

3.6.2.2 FLIGHT CONTROL INFORMATION DISPLAYS

REQUIREMENTS

3.6.2.2 Flight Control Information Displays. Vehicle flight information displays for manual flight control shall include, as a minimum:

- Altitude
- Altitude rate
- Heading
- Pitch, roll attitudes with horizon information
- True airspeed
- Vehicle maneuvering parameters which are hazardous if limits are exceeded (i.e., stall-angle of attack, normal acceleration - g's).
- Video displays for orientation and motion cues during visual targeting-oriented flight phase tasks (i.e., landing, weapon delivery). See requirement 3.6.4.3.

DISCUSSION

The first five flight parameters represent the basic information requirements for the operator to fly the vehicle. This section does not try to specify additional flight parameter information displays which may be required to accomplish specialized manual functions, such as landing or weapon delivery. When such requirements are established they will be included under Specialized Flight Phase Displays (Section 3.6.4).

Maneuvering limitations which can be exceeded by operator and result in unsafe vehicle operating conditions must also be displayed. Because limits will vary from one RPV configuration to another, this display requirement will be established by the contractor with agreement of the procuring activity. The main intent of this present requirement is to identify the need and to insure adequate consideration.

Further, minimum flight control information displays really depend on the type of vehicle and mission. It is recommended that future development of RPV criteria consider expanding this requirement by vehicle class which in turn generally implies mission type.

3.6.2.3 VIDEO DISPLAY UPDATE RATES

REQUIREMENT

3.6.2.3 Video Display Update Rates. When video displays are used, they shall be capable of providing the following minimum information update rates unless otherwise specified.

The frame rate at the operators display shall be restored (refreshed) as necessary to avoid flicker.

Flight Phase	Task	Minimum Video Information Update Rates
A	General Recce, Surveillance, Bomb Damage Assessment	3 frames/sec.
	Weapon Delivery	7.5 frames/sec.
	Precision Tracking	7.5 frames/sec.
C & D	Approach and Landing	7.5 frames/sec.

DISCUSSION

Information update rates are important to the operator for good flying qualities. Video update rates are particularly important because they provide the only motion cues. In addition, the video data transmission requirements can have a significant impact on data link design. The following summarizes some data link updates rates considered in different studies for different types of flight phase tasks. These data formed the preliminary basis for requirement 3.6.2.3.

Enroute Navigation/Guidance Updates. The update information rate used in the enroute/return navigation update studies (References 23 and 25) was 5 seconds. It should be noted that this update rate refers to navigation and status information and not transmission rates for video data. The 5 second update does not seem unreasonable for general monitoring and navigation updates during enroute flight phases providing the operator is not required to perform critical and precisely-timed maneuvers.

Precise Tracking. Fixed base air combat simulation studies of Reference 26 examined the effect of visual feedback time delays on operator tracking performance. Acceptable video time delays were defined as delays which did not significantly affect the results, or the manner in which the subject 'flies' the simulator. The subject maneuvered his pursuit aircraft in 5 degrees of freedom (forward speed of target and pursuit aircraft were constant) to track a target airplane as it oscillated in the pitch plane.

Results and conclusions were:

1. The acceptable time delay appears to be related to the frequency and damping of the short term longitudinal mode of the simulated aircraft (lateral characteristics were held constant). In general, the acceptable time delay decreased as pilot rating increased (that is, as handling qualities became less desirable).

2. Even small time delays can have an adverse effect on operator performance for some vehicle configurations. For the range of vehicle parameters studied, the maximum time delay which could be tolerated (without affecting the subject's performance or operating procedure) was about 0.141 second.

3. Increasing task complexity or degrading the vehicle handling qualities reduces the acceptable level of visual-scene time delays.

Recce-Target Acquisition. Reference 27 studied the effect of video frame rates of 24, 8, 3 and 1.0 frame per second upon target acquisition range and acquisition probability. Figures 17 and 18 summarize results. The principal conclusion was that there was no real, i.e., statistically significant, reduction in operator performance in going from 24 image frames/second down to 1 frame/second. In the absence of appreciable video noise, the data showed no loss not attributable to chance in either acquisition range or target acquisition probability.

Simulation studies conducted by Boeing (Reference 21) confirmed that orientation (briefing) pictures were important and useful in locating prominent features prior to actual target detection. With this familiarization, simulation studies found that a fixed frame rate of one picture per second would not substantially reduce operator target detection capability.

Strike-Weapon Delivery. Sperry man-machine studies (Reference 14) indicated that 7.5 frames per second would be adequate for vehicle and E. O. weapon sensors.

The Hughes DCDRS report (Reference 18) states that operator performance does not appreciably deteriorate until video frame rates fall below 7-8 frames per second; however, frame rate at the display must be restored (refreshed) to avoid flicker.

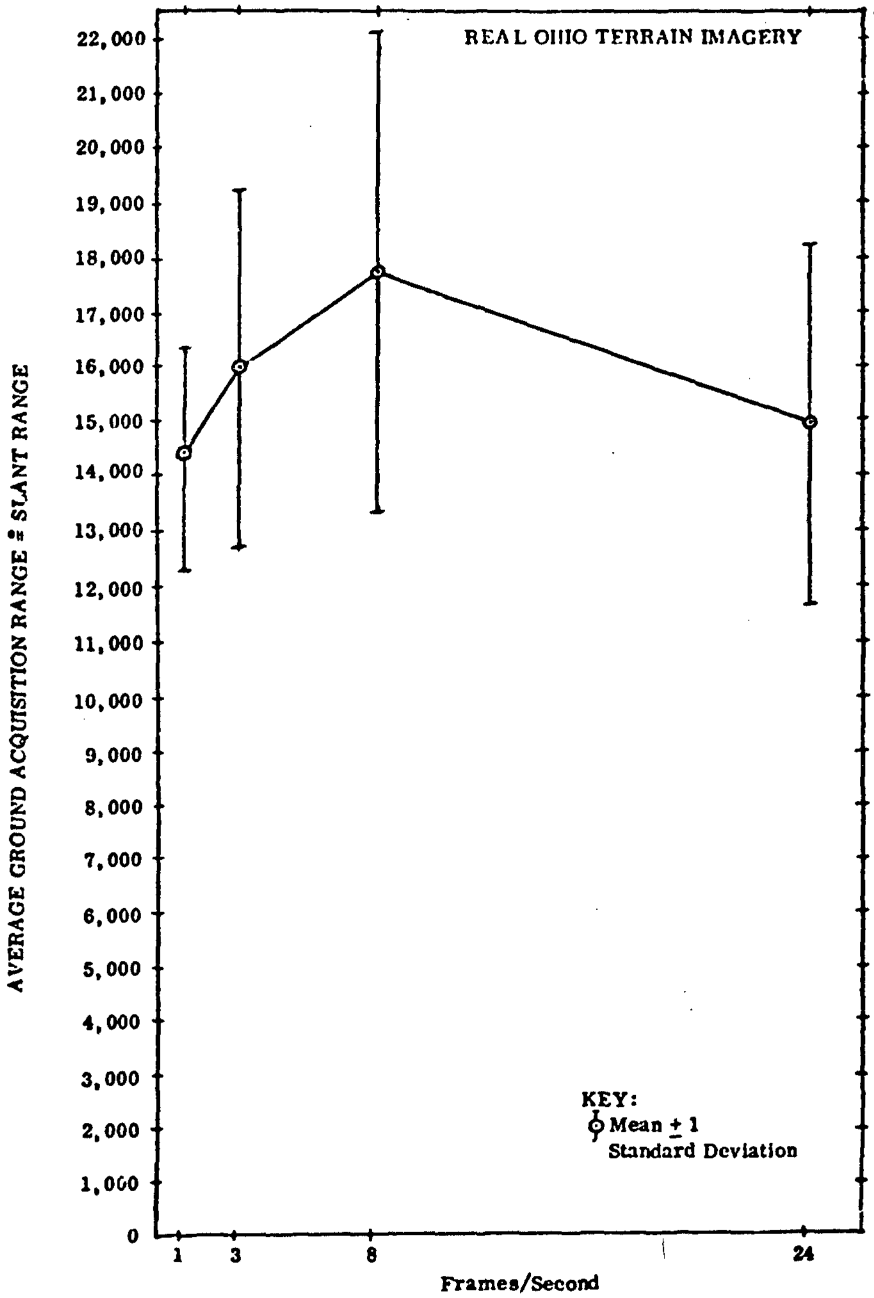

Figure 17. Average Ground Acquisition Range Using Imagery Collected From An Aircraft. Due to the Low Camera Declination Angle, The Slant And Ground Ranges Are Within One Percent Of Each Other. (Reference 27)

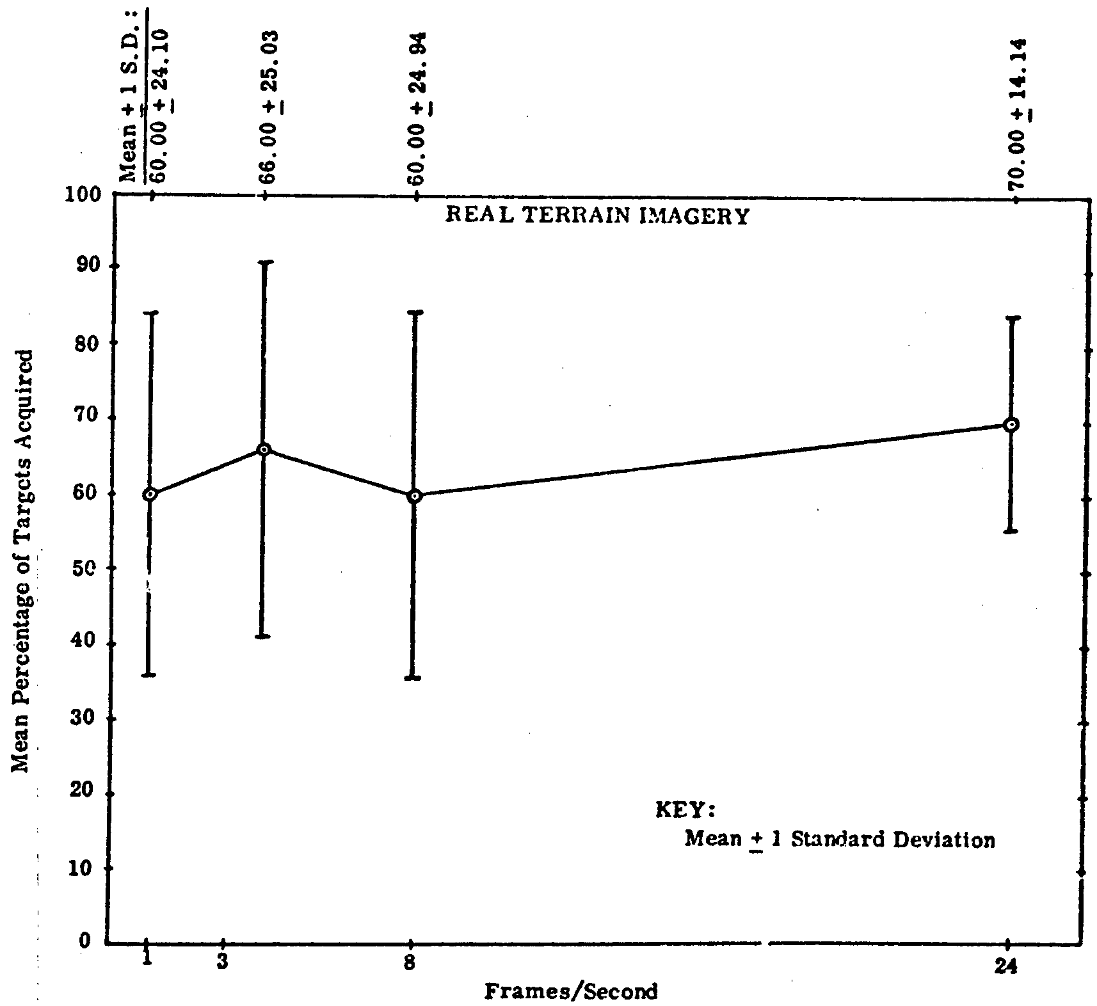

Figure 18. Percentage Of Targets Acquired By the Average Observer At Various Frame Rates For Imagery Collected With An Aircraft Flying Over Real Terrain.

3.6.3 OPERATOR CONTROLLER CHARACTERISTICS

REQUIREMENT

3.6.3 Operator Controller Characteristics. Critical vehicle control and command functions, and display mode or format selections, shall be provided as dedicated, fixed-function controls.

DISCUSSION

Table 17 summarizes control functions by mission phase and function. The table is an extraction from Reference 14 except for the additional consideration for Ground Display Format/Mode Selection and Operational Controls. Although further modification and refinement of this table is needed for consistency, it is felt that such a format is useful for identifying dedicated manual control design requirements.

It is necessary to be able to call up display formats, address vehicle and implement critical vehicle commands as quickly as possible. Use of a keyboard for many functions of these types is too time-consuming to be considered. Dedicated function controls permit rapid display callup and initiation of critical command functions.

TABLE 17. REMOTE CONTROL STATION-CONTROL REQUIREMENTS AS A FUNCTION OF MISSION PHASE (Reference 14)

MISSION / FUNCTION	STRIKE	ENROUTE (NAVIGATION)	LAUNCH & RECOVERY	IMPLEMENTATION
Steering	(1) Sensor-Designator (2) Weapon (3) Vehicle (a) Pitch Up/Down (b) Turn Right/Left (c) Straight and Level	(1) Sensor-Designator-Update (2) Vehicle (a) Pitch Up/Down (b) Turn Right/Left (c) Straight and Level	(1) Sensor (Runway Landing) (2) Vehicle (a) Pitch Up/Down (b) Turn Right/Left (c) Straight and Level	Control Stick
Sensor Control	(1) Zoom In/Out	(1) Zoom In/Out	(1) Zoom In/Out	Integrated with Control Stick
	(2) On/Off (3) Image Enhancement (4) Image Reversal	(2) On/Off (3) Image Enhancement (4) Image Reversal	(2) On/Off (3) Image Enhancement (4) Image Reversal	Dedicated Legend Push-buttons
	(5) Contrast (6) Gamma (Video Gain)	(5) Contrast (6) Gamma (Video Gain)	(5) Contrast (6) Gamma (Video Gain)	Dedicated Switch
Weapon Control and Stores Management	(1) Lock-On (2) Weapon Release			Integrated with Control Stick
	(3) Weapon Type (4) Weapon Select (1 of 4) (5) Arm-Safe (6) Weapon Warm-Up/Cool (7) Fuzing (8) Cage/Uncage			Programmed (Reformattable) Pushbutton Indicators
Ground Display Format/Mode Selections and Operational Controls	(1) Contract (2) Brightness (3) Status display Selections (4) Orientation/situation display mode (5) Control data input formats (6) Weapon or Vehicle sensor video	(1) Contract (2) Brightness (3) Status display Selections (4) Orientation/situation display mode (5) Control data input formats	(1) Contract (2) Brightness (3) Status display Selections	Dedication Switches/pushbutton
Flight Modes	(1) Preprogrammed Flight (1,2,3,4) (2) Attitude Hold (3) Airspeed Hold (4) Navigation Update (5) Weapon Delivery	(1) Preprogrammed Flight (1,2,3,4) (2) Attitude Hold (3) Airspeed Hold (4) Navigation Update	(1) Preprogrammed Flight (1,2,3,4) (2) Attitude Hold (3) Airspeed Hold (4) Engine On/Off (5) Ready to Launch (6) Launch (7) Arm Recovery (8) Engage Recovery (9) Three Speed Brakes (10) Flaps (11) Brakes	Dedicated Legend Pushbuttons
	(6) Commanded Altitude (7) Commanded Ground Track (8) Commanded Ground Speed	(5) Commanded Altitude (6) Commanded Ground Track (7) Commanded Ground Speed	(12) Commanded Altitude (13) Commanded Ground Track (14) Commanded Ground Speed	Keyboard
	(9) Airspeed Increase/Decrease	(8) Airspeed Increase/Decrease	(15) Airspeed Increase/Decrease	Dedicated Switch
Flight Reprogramming	(1) Checkpoint Insertion (4 variables)	(1) Checkpoint Insertion (4 variables)	(1) Checkpoint Insertion (4 variables)	Keyboard
Communications	(1) Intercomm Channel Sel (2) Mike Switch (3) Vox	(1) Intercomm Channel Sel (2) Mike Switch (3) Vox	(1) Intercomm Channel Sel (2) Mike Switch (3) Vox	Dedicated Switch
	(4) Data Link Channel (5) UHF Channel Freq Select	(4) Data Link Channel (5) UHF Channel Freq Select	(4) Data Link Channel	Keyboard

3.6.3.1 FORCE/DEFLECTION GRADIENTS

REQUIREMENTS

3.6.3.1 Force/Deflection Gradients. The force gradients shall be essentially linear and within the limits of Table 18.

TABLE 18. RANGES IN HAND CONTROLLER FORCE/DEFLECTION GRADIENTS*

AXIS	ALLOWABLE FORCE GRADIENT
Longitudinal (Lb/Deg)	.02 to .2
Lateral (Lb/Deg)	.02 to .2
Directional Twist Moment (In-Lb)	0.01 to .5

*Preliminary values, more study required

3.6.3.2 Control Centering and Breakout Forces. Longitudinal, lateral, and directional controls should exhibit positive centering at any normal trim setting. The combined effects of centering, breakout force, and force gradient shall not produce objectionable flight characteristics, such as poor precision-tracking ability.

3.6.3.3 Control Free Play. The free play in each control, that is, any motion of the control which does not move the control surface in flight, shall not result in objectionable flight characteristics, particularly for small-amplitude control inputs.

DISCUSSION

The RPV hand controller force/motion characteristics are described by three requirements: Force/Deflection gradients, Control Centering and Breakout Forces, and Control Free Play. The force/motion characteristics of the controller are important factors in influencing handling qualities. There is a lack of documentation on optimized force characteristics and their relationship to flight control tasks. A survey of side arm controllers is given in Reference 28. Hand controller force-motion characteristics for specific RPV simulation studies are summarized in Table 19. It appears that many simulation studies which used hand controllers take what they have, or adjust characteristics to operators' liking and continue on with the intent of the study. Unfortunately controller characteristics can influence task performance as well as cause the loss of closed-loop system stability (operator-induced oscillations). A rough survey indicates that these gradients vary by as much as a factor of ten. How much is due to the controller type (pivot point), the task being performed, or the natural range of acceptance by the

TABLE 19. HAND GRIP CONTROLLER FORCE MOTION CHARACTERISTICS SPECIFICALLY USED IN RPV SIMULATIONS

Flight Phase Task	FORCE GRADIENT			MAX. MOTION			MAX FORCE			BREAK OUT FORCE		
	PITCH (LB/DEG)	ROLL (LB/DEG)	YAW (IN-LB)	PITCH (DEG)	ROLL (DEG)	YAW (DEG)	PITCH (LB)	ROLL (LB)	YAW (IN-LB)	PITCH (LB)	ROLL (LB)	YAW (IN-LB)
(Smart) Weapon Delivery AFFDL/FGC STUDY (PRELIMINARY)	.16	.16	.45	±18	±18	±20	±2.8	±2.8	±9.2	-	-	-
Reference 9* Landing Approach Study	.02	.03	-	30 (Nose Up)	28 Left	±55	0.7 (Nose Up)	.75 Left	-	.02	.02	NEGL.
				20 (Nose Down)	35 Right		0.5 (Nose Down)	.95 Right				
FACILITY 1							1.7	1.1	7.5	.4	.25	NEGL.
FACILITY 2							.6	.8	.7	.02	.02	NEGL.

* Three sets of data are given. Facility 2 and the controller used in Landing Approach study appear to be the same (not clear in report).

operator is unknown at this point. Because the gradients will also be affected by how much motion is available or required, it may be better to state a maximum force requirement rather than gradients, as presently proposed. The maximum force requirement will probably depend on the class of the vehicle, since this determines usable load factor.

3.6.3.4 CONTROLLER INPUT RESPONSE (SENSITIVITY)

REQUIREMENTS

3.6.3.4 Controller Input Response (Sensitivity). There shall be no objectionable nonlinearities in vehicle response to control inputs by the operator. The control input response shall meet requirements given in Tables 20 or 21 depending on type of command system used.

3.6.3.4.1 Rate Command Response. The maximum vehicle rate response per unit deflection of operator hand controller shall lie within the values of Table 20.

3.6.3.4.2 Attitude Position Command Response. The maximum vehicle attitude change per unit deflection of operator hand controller shall lie within the values of Table 21.

DISCUSSION

Aside from vehicle stability, control sensitivity is probably one of the most important flying quality parameters in that improper selection can degrade the flying qualities of an otherwise satisfactory vehicle to an unacceptable level. Conversely, judicious selection of control sensitivities for vehicles having marginal handling qualities can result in considerable improvement in the opinion of the operator (Based on aircraft experience). Generally speaking low sensitivities result in sluggish response characteristics while high sensitivities tend to lead to overcontrolling.

The term 'control sensitivity' is usually defined as vehicle angular or linear acceleration per unit control displacement. In addition to the fact that such control sensitivities would be difficult to determine experimentally for validation, acceleration is not a motion characteristic that a remote operator can easily relate to (if at all) when using video for visual reference. This becomes particularly obvious for attitude rate command systems where the vehicle rotational rate is automatically controlled and is proportional to controller displacement.

The vehicle acceleration to the commanded rate will not be perceived by the operator unless the control power is so low that significant time elapses before the commanded rate is achieved. The visual cues which the operator does respond to are position errors and the motion (rate) at which the position changes. Intuitively, the motion characteristics which the operator likes best are those that he can follow without losing orientation and can anticipate sufficiently to prevent undesirable overshoots. Operator's opinions may also change depending on the type of task he is to perform, and whether large or small position changes are involved. He may desire higher response rates for tasks involving large maneuvers and/or rapid control.

TABLE 20. RATE COMMAND - VEHICLE RATE RESPONSE (DEGREES/SECOND) PER DEGREE DEFLECTION OF HAND CONTROLLER.

Level	Pitch		Roll		Yaw	
	Min	Max	Min	Max	Min	Max
1						
2						
3						

TABLE 21. POSITION COMMAND - VEHICLE ATTITUDE RESPONSE PER DEGREE DEFLECTION OF HAND CONTROLLER.

Level	Pitch		Roll		Yaw	
	Min	Max	Min	Max	Min	Max
1						
2						
3						

It is recommended that the control sensitivities be expressed indirectly in terms of vehicle response; units would be degrees/second, or degrees per unit displacement of operator controller. The former would apply to rate command systems and the latter to position command systems. For Level 3, old fashioned airplane - type control may be considered: control surface motion per stick motion, where a given deflection produces a rate that varies with speed.

The above requirement considers the two likely control methods.

Several investigators have studied both, but they did not publish the sensitivities used. Strike RPV display and control studies of Reference 29, found that the position control stick (vehicle attitude in direct proportion to stick deflection) was superior to the conventional rate control stick. All subjects, from inexperienced nonpilots to Navy pilots, demonstrated better performance with the position stick in terms of the crucial target approach maneuver. Navy pilots benefited least because of their greater flight experience. The conclusion of the report was that the simpler, more direct relationship between control deflection and vehicle attitude was beneficial. The position stick gave the operator sensory attitude feedback thus minimizing the need for visual contact with the attitude display.

Recent AFFDL/FGC RPV landing and approach studies (Report to be published) indicated that the operators accepted position control in roll (generally a nulling task), but disliked such control in the pitch axes which required the operator to hold off-null control positions. Trim capability (reset to null) could alleviate this problem.

The tables for the control response requirements contain no values because of a lack of available data. As data become available, from future simulation studies and actual experience, it is possible that these requirements may be expanded into several tables which are a function of flight phase (i.e. Approach and Landing, Weapon Delivery).

3.6.3.5 CONTROLLER HARMONY

REQUIREMENT

3.6.3.5 Controller Harmony. The control forces, displacements, and sensitivities of the pitch, roll and yaw controls shall be compatible, and their responses harmonious. Intentional controller inputs in one axis shall not result in inadvertent inputs to the other axis.

DISCUSSION

The requirement is intended to provide ease of control in maneuvering the vehicle. Lack of an adequate data base precludes a quantitative requirement. "Controller harmony" implies a satisfactory relationship among the pitch, roll and yaw controls in terms of angular response of the vehicle per unit control force, deflection, etc.

A desired characteristic is that the pitch and roll control forces be in the proper ratio, to enhance proper coordination of maneuvers. Further, unless the pitch and roll control sensitivities and breakout forces are properly matched, intentional inputs to one control can result in inadvertent inputs to the other.

3.6.4 SPEC:ALIZED FLIGHT PHASE DISPLAYS AN) CONTROLS

REQUIREMENT

3.6.4 Specialized Flight Phase Displays and Controls.

DISCUSSION

The following subsections discuss display and control requirements for the principal operational phases: Enroute (navigation) phase, Terminal target oriented mission flight phases (weapon delivery), Launch, and Recovery.

The general conclusions of the man-machine interface studies lead to the recommendation that an 'area control' approach be used; different operators using specialized displays and controls are responsible for separate launch, recovery, enroute, and terminal strike mission flight phases. Based upon this rationale, it was decided to provide for display and control requirements as they relate to specific operational areas. It is recognized that simpler RPV air-vehicle systems may combine operator tasks. However, presenting display and control requirements for each major task provides a more straightforward identification of the design criteria. Comparison of these requirements, in terms of commonality and task difficulty, will provide guidelines for combining display, control, and operator functions for various RPV air-vehicle systems.

3.6.4.1 ENROUTE NAVIGATION/GUIDANCE DISPLAYS

REQUIREMENT

3.6.4.1 Enroute Navigation/Guidance Displays. The guidance/navigation displays shall provide sufficient information of the predetermined mission flight plan and the actual vehicle position, altitude and velocity vector to enable operator to monitor adequately the vehicle/mission performance and flight progress. When required, they shall also enable the operator to perform navigation updates or select alternate flight plans. Table 22 identifies display information considerations.

DISCUSSION

The navigation/guidance displays are required to provide the following types of information and capabilities which will enable an operator to perform navigation monitoring, navigation/guidance position updates, and status monitoring (See 3.6.2.1) of selected subsystems:

- Provide orientation information for monitoring real-time mission performance and progress of vehicle(s) under controller responsibility
- Provide information for manual back-up navigation
- Modify or select alternate mission flight plans
- Provide cueing where required for control functions (e.g. operator handoffs, stores jettison etc.)
- Provide rapid and clear presentation of status data, and any control input formats required for data update insertion

The intent of Table 22 is to identify major display parameters for an enroute controller display. Actual display methods, content and format will understandably vary with the particular RPV system capabilities and mission. The most important display consideration is clear and concise presentation of necessary information.

The information requirements are based on the recommended normal mode of operation, which is automatic preprogrammed flight control with manual override capability. The automatic preprogrammed recommendation is a rather obvious conclusion of all man-machine allocation studies. The fatigue and complexity involved in flying and navigating an RPV particularly on long missions and in low-altitude terrain-avoidance situations (normally desired for survival) precludes the use of manual control as the prime mode for most RPV operations.

TABLE 22. PRIMARY NAVIGATION/GUIDANCE DISPLAY INFORMATION CONSIDERATIONS

Information	Comments
Mission Flight Plan	
• Planned ground track showing significant way points, targets, and important event points	Required
• Altitude	Required
• Airspeed	Required
• Time schedule (i.e., TOA'S)	Required for time-dependent missions
Map Background Information	
• Major geographical obstacles/features	As required for mission
• Boundaries (Political, flight corridors, etc.)	
Actual Vehicle Position and Velocity Vector Information	
• Vehicle position sufficiently referenced to planned ground track to enable determination of navigation errors for update commands.	Required
• Actual vehicle ground track direction (ψ_g)	Desirable
• Vehicle heading	Secondary-informative
• Airspeed	Required
• Ground Speed	Secondary-informative
• Altitude	Required
• Actual time schedule (i.e., ETA'S next waypoint or significant event and or time schedule deviations)	Required for time dependent missions.
Operator Alerting (See 3.6.2.1)	
• Guidance errors unsatisfactory	Desirable for multi RPV control
• Vehicle subsystem Malfunctions	Required
• Data link outage (narrow band uplink or downlink, wideband video)	Required

As a result, the principal enroute controller tasks will essentially consist of monitoring critical functions which define mission performance/progress and RPV status, performing navigation position updates, and modifying or selecting alternate mission flight plans. Judgemental override decisions will also be required by controller when system malfunctions, or environmental or mission contingencies, occur. Backup systems should be activated automatically with manual override capability.

For multiple RPV control an enroute operator should not be required to monitor and update more than four to five RPVs at one time. Hughes DCDRS trade studies estimate that each enroute controller can monitor up to six or seven automatically controlled RPVs, and 10 in contingency situations. Reference 23 concluded that enroute operators, monitoring and updating automatically controlled vehicles can be expected to control three to four RPVs effectively, and more than five RPV's with very little effectiveness. Reference 30 determined that each enroute operator could successfully monitor and control five RPV's simultaneously.

Various information displays using combinations of dials, meters, graphics, and alphanumerics have been proposed or studied. The general overall displays approach is a graphic-alphanumeric display with a minimum of dials and meters for the enroute controller. This allows the operator to concentrate on one display methodology without having to look around and interpret other displays forms. It appears that a judicious selection of symbols with graphics, and alphanumeric data with dedicated locations on the display, would be adequate format for presenting data requirements to the enroute controller. Several enroute situation displays are discussed in detail in the man-machine, DCDRS, and AMRL simulation studies (References 15, 23, and 24; respectively).

3.6.4.2 MANUAL NAVIGATION UPDATE CONTROL

REQUIREMENTS

3.6.4.2 Manual Navigation Update Control. When navigation updates are required one of the following control input capabilities for initiating the command inputs shall be considered:

- Entry of navigation data in numeric form (i.e. keyboard)
- Entry of navigation commands from graphics (i.e., cursor)
- Manual initiation of automatically computed navigation updates (i.e. dedicated function key).

DISCUSSION

The above requirements basically identify three likely considerations for manual navigation updating which involve slightly different control interfaces. The method used will depend on the system; however, each offers certain advantages.

The first of the three methods provides a precise method for entry of position data and provides flexibility to handle other commands such as airspeed, altitude, and position information for flight plan reprogramming. The cursor approach is faster, but usually results in less accurate position inputs. The resolution accuracy of the map display is an important consideration when using cursor commands in graphic form.

The third approach, essentially one step away from fully automatic updates, would provide the fastest update capability. This could be used when numerous position updates are required or the operator work load requires a rapid semi-automatic update capability (e.g. multi-vehicle operation).

The type of data input commands will depend on the degree of update to be performed. Modification or reprogramming of automatic flight plans will require three basic types of data inputs: altitude, airspeed and position information defining the desired ground track.

It is possible for the position information to be entered in two different forms: X, Y waypoint grid coordinates, or ground track heading angle and track distance to be travelled along that heading (polar coordinate type information). The more conventional grid coordinate approach is recommended since it is directly compatible with standard display information. Grid coordinates can be easily determined and do not require additional calculations to determine angles and distances.

3.6.4.3 APPROACH AND LANDING FLIGHT CONTROL DISPLAYS

REQUIREMENT

3.6.4.3 Approach and Landing Flight Control Displays. Flight parameter information to be displayed for manually-controlled approach and landing tasks shall include:

- Video display for orientation and visual cues
- Airspeed
- Altitude
- Altitude rate
- Vehicle attitudes - pitch and roll attitudes with horizon information.
- Vehicle maneuvering limits if critical (i.e. stall warning, "g" loading).

The following additional display information is recommended to insure precise and consistent landing capability:

- Glide slope and localizer (azimuth) information.
- Integrated display of height above ground and vertical touchdown velocity (particularily applicable to flare landings).

DISCUSSION

The mode of recovery and location of the recovery operator will dictate display requirements. The wide variety of recovery methods (i.e. parachute, net capture, operator at recovery site using direct visual aids, or remote operator), and types of vehicles will require display information unique for that system.

The video display requirement applies to a recovery operator who has no direct outside visual contact, performing a conventional type landing. It also appears that when landing RPV's from a remote control center, the operators do not perceive altitude with sufficient precision when they are getting low in the landing approach. Reference 31 investigated several landing information display combinations. Although landings were performed without glide slope information or an integrated display of height above ground and vertical touchdown velocity, the use of such displays gave the operators (pilots)

greater assurance of success, and these displays were found to be extremely useful in controlling the vehicle during final approach and landing.

Although not specified herein, consideration must also be given to the form in which the flight information is provided to the operator. Conventional instruments and tape dials can be used to support the video display, or the information can be superimposed on the display using alphanumerics and guidance symbology. The trend in manned aircraft is toward providing the necessary information on ILS type displays (Reference 32). Specific RPV approach and landing display studies of Reference 31 indicate that pilots' acceptance tends to increase with the addition of guidance symbology directly on the display; however, clutter must be avoided. Pilots complained that the use of instruments resulted in more exhaustive workload because of concentration and eye focusing on instruments to obtain the same quickening cues normally obtained from outside vision and motion cues.

3.6.4.4 WEAPON DELIVERY (STRIKE) DISPLAYS AND CONTROLS

REQUIREMENT

3.6.4.4 Weapon Delivery (Strike) Displays and Controls. Dedicated displays and controls shall be provided to enable the operator to perform those vehicle flight control and weapon control functions required to successfully acquire, track, designate, and release weapon. Dedicated control requirements of 3.6.3 shall be considered, where applicable.

DISCUSSION

The various operational analysis and man-machine allocation studies have established that tasks such as target search, detection, acquisition, attack steering, and weapon lock-on should be done manually (References 14, 15, 16, 18, 24, and 29). These tasks, in general, are likely to involve judgemental decisions and contingencies which will require manual override control to insure mission success. The strike operator should be completely dedicated to the strike vehicle; his primary task is to assure that the appropriate weapon is delivered against the correct target.

The high degree of concentration needed for manual control tasks (i.e. detection, attack steering, etc.) dictates freeing the operator as much as possible from actually flying the RPV. Automatic guidance and flight control assist modes (e.g. altitude, terrain following, attitude, airspeed) should be used to control the RPV unless manual overrides are exercised by the controller.

The above display and control requirement for weapon delivery is general in nature because strike displays and controls are highly unique to the type of target-oriented mission, the weapon involved, and the type of vehicle control. The two basic types of weapon delivery are guided and unguided, with several possible combinations of operator/vehicle sensor/weapon sensor interfaces. For an unguided weapon the vehicle must be aligned with the target before weapon release, but for a "smart" weapon the vehicle need only be within the launch envelope of the weapon. Functionally, during the attack phase two image sensors may be involved if an E.O. type weapon is used (vehicle and weapon sensor). In addition, the primary vehicle image sensor may be either fixed to airframe or gimballed (slewable).

Three principal methods of vehicle control are: preprogrammed automatic, sensor following (vehicle commanded by sensor signals), and manual control in which the operator directly flies the vehicle.

Table 2? identifies combinations of vehicle control, and sensor characteristics (vehicle and weapon) which are felt to be most compatible, and generally identifies the principal operator control functions which must be provided.

The general recommendation is that the sensor following mode be used for either a guided or unguided weapon delivery. The operator does not have to

TABLE 23. RECOMMENDED STRIKE SENSOR CONTROL

Weapon Delivery	Vehicle Control	Video Sensors: Vehicle Sensor	Video Sensors: Weapon Sensor	Operator Functions
Unguided Weapon	Automatic Preprogrammed	Not Required	N/A	Monitors, updates navigation and/or target coordinates using enroute displays
	Sensor Following Mode Vehicle commanded by sensor gimbal angles or pipper position	Sensor with manual slew capability	N/A	Aligns sensor on target
		Body fixed	N/A	Aligns pipper on tgt.
	Manual control (with automatic assist modes)	Body fixed	N/A	Flies vehicle to align sensor on target
Guided Weapon	Automatic Preprogrammed	Sensor with manual slew capability	. Slaved to vehicle sensor . Manually slewable for final lockon corrections	Aligns vehicle sensor on target and locks on using weapon sensor
	Sensor following	same as unguided	"	"
	Manual control (with automatic assist flight modes)	Body Fixed (Initial alignment)	"	Flies vehicle for initial alignment. Lock on using weapon sensor

be concerned with interpreting visual and/or flight instrument displays to fly the vehicle. He needs only to align the sensor with the target. A gimballed (slewable) sensor or body fixed sensor with manual pipper could be used. Slewing may be desirable, when complexity permits, to increase visual capability and possibly reduce navigation accuracy requirements. When direct manual flight control is used the vehicle video sensor should remain in fixed alignment with the vehicle axes (body-fixed). Because of the increase in operator workload, direct manual control should primarily be considered as a backup mode. In any case, automatic flight control assist modes such as altitude, heading, pitch and roll attitudes and airspeed hold modes should be used as applicable, which the operator overrides with manual input commands.

The above rationale is generally supported by the study findings, of References 14, 15, 16, 18, 22, and 29.

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APPENDIX A

A REVISED ATMOSPHERIC DISTURBANCE MODEL FOR USE IN MILITARY FLYING QUALITIES SPECIFICATIONS

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I. INTRODUCTION

Flying qualities are normally a compromise between requirements for stability on one hand and for maneuverability on the other hand. Although this trade-off is not simple it is a far more complex problem to ensure good flying qualities in turbulence and other atmospheric disturbances. The range of atmospheric disturbance possibilities is infinite, in practice. Much work has been done in the past and is being done currently to measure, correlate and model atmospheric disturbances. Reference A-1, for example, lists 269 further references.

An effort is currently underway to revise the flying qualities specification for piloted aircraft (Reference A-2). This Appendix discusses the problems of flying qualities relative to atmospheric disturbances and presents the rationale for the proposed revision of the appropriate sections of MIL-F-8785. Although the discussion is specifically related to MIL-F-8785B the actual disturbance model proposed is more generally applicable. In particular, all or any part of the model could be applied to RPV design and analysis, as required by the procuring activity.

II. PHILOSOPHY

For the purposes of flying qualities specifications an engineering model of atmospheric disturbances is required. This engineering model may be considered as the simplest model which correctly identifies the primary parameters of particular interest. It is then hoped that secondary parameters do not alter the results and tertiary parameters are not recognized. This is in contrast to the objectives of basic research into meteorological phenomena or the physics of atmospheric dynamics. It is also noted that terminology has different connotations depending on an individual's background or field of endeavor. To prevent any confusion, certain terms will now be defined for use in interpreting the proposals contained herein.

Mean Wind. This is the steady wind or the reference value on which perturbations are superimposed. The mean wind could vary with time and spatial coordinates, but is considered to be only a function of altitude. Since for engineering purposes the mean wind is constant with time, the meteorological concept of "averaging time" does not apply. There is no requirement for the "mean wind" to actually be a mean over any particular time period.

Wind Shear. This is the rate of change of the magnitude of the mean wind with altitude.

Vector Shear. This is the rate of change of the direction of the mean wind with altitude.

Turbulence. This term is used to denote the continuous, random fluctuations in wind velocity which must be described statistically. Actual atmospheric turbulence has been shown to be non-Gaussian, however, for the current purposes turbulence is assumed to be random with a normal, or Gaussian, distribution.

Gust. This term is used to denote a discrete or deterministic change in the wind velocity. In application gusts may be used independently or superimposed on a mean wind and/or turbulence to represent large disturbances. Used appropriately a gust can actually represent a discrete wind shear such as can occur at a temperature inversion; the large (3σ or 4σ) fluctuations that occur in actual turbulence but which are not represented in the assumed Gaussian form of turbulence; the fluctuations due to the wake of man-made or topological features; or an independent discrete phenomenon such as the wing tip vortex of another aircraft. At this point a form of gust will not be prescribed.

The above definitions depart from meteorological practice in order to allow some flexibility in defining models of atmospheric disturbances that are tractable for engineering analyses. Although the desirability of tractability should be obvious, the requirement for flexibility is considered to be equally desirable. During the course of a vehicle development a variety of analyses, computer simulations, piloted simulations, etc. are performed with different objectives and different requirements for atmospheric disturbance inputs. The definitions given earlier identify and separate the primary parameters in atmospheric disturbances which relate to aircraft control and flying qualities. The synoptic effect of any or all of these parameters can also be obtained. Ultimately, it is suggested that a piloted simulation should be performed which does combine all the above elements and has the best possible representation of atmospheric disturbances.

The "best possible representation" of atmospheric disturbances is probably not going to be achieved by combining Gaussian turbulence with discrete gusts - better and better approximations would be achieved using more and more complex specifications for the gusts. The non-Gaussian character of actual disturbances has previously been alluded to and is also supported in numerous other reports (e.g. References A-3 through A-5). In contrast, the author of Reference A-1 expresses the opinion that "if the three items listed had been handled more realistically, then nonstationarity aspects may not be important". The use of non-Gaussian turbulence in simulations has also yielded mixed results. For the flying qualities study reported in Reference A-6 the pilot chose a non-Gaussian turbulence representation as being more realistic than the Dryden form of Gaussian turbulence. Reference A-7 showed no conclusive results in an attempt to develop a non-Gaussian model. There are also a variety of approaches to developing a non-Gaussian representation. It can safely be stated,therefore, that there is no unanimous opinion with respect to any departure from a Gaussian distribution of disturbances. In fact, the atmosphere itself does not have a uniquely non-Gaussian characteristic. Using the fourth order moment as a measure of "non-Gaussianess" Reference A-8 indicates a wide range of values including Gaussian. The most significant point to be made here is that the atmospheric disturbance model to be used, for instance in a piloted ground-based simulation, should be consistent with the objectives of the simulation and the fidelity of the total system representation. The attempt in the current revision of MIL-F-8785B will not be to define a universal model but to identify the primary parameters of atmospheric disturbances. Thus non-Gaussian disturbances are suggested but not rigidly defined allowing flexibility in application.

Reference A-2 states that the atmospheric disturbance models shall be used - "to assess:

a. The effect of turbulence on the flying qualities of the airplane;

b. The ability of a pilot to recover from the effects of discrete gusts."

There were no criteria, however, to judge the acceptability of any effects of turbulence on flying qualities. It is now proposed to define three levels of atmospheric disturbance and to recognize the degradation of flying qualities that occurs with increasing turbulence. The different atmospheric disturbance levels are denoted "LIGHT, MODERATE, and SEVERE". Although there is no exact correspondence to the levels of flying qualities, there is a similarity in principle. Thus the light disturbances should not increase pilot workload significantly and therefore should not degrade the pilot opinion relative to calm air. "Pilot opinion" here is considered in the total sense of performing a given task with a particular aircraft system in a certain atmospheric environment. The atmospheric disturbances are a part of the task and increasing the intensity of the atmospheric disturbances increases the pilot workload, or alternately decreases pilot performance, in carrying out the task. Pilot opinion, whether the result of piloted simulation or analytical prediction, is affected by aircraft characteristics and by the intensity of atmospheric disturbances. The pilot opinion, workload or performance corresponding to basic (i.e. calm air) characteristics of Level 1, 2 or 3 should not degrade out of that level in light disturbances. Successive degradation in pilot opinion will be allowed in light, moderate and severe disturbances. For the normal aircraft state (no failures - Level 1 flying qualities) it is proposed that moderate and severe disturbances may cause degradations equivalent to Level 2 and 3 flying qualities. It is now necessary to recognize characteristics worse than the "Level 3" currently defined in MIL-F-8785B. With a degraded aircraft state in severe disturbances which correspond to typical thunderstorm activity, the minimum requirement would be that control of the aircraft can be maintained, although not all the Category B and C flight phases could necesssarily be completed.

Turbulence becomes less and less continuous in the statistical sense as the intensity increases, but can be expected to occur more in patches. The severe disturbance can therefore be used to show that control is sufficient "to fly out of a patch". To quote from Reference A-9 "...information on the lengths of patches of turbulence is lacking, it is reasonable to assume for calculation purposes that patches having constant reference intensity are typically 5 miles across. However, it should be noted that the conditions favoring the development of turbulence normally extend over areas measured on a synoptic scale and that as a consequence turbulence patches cluster both in time and in space. This makes it difficult for instance to estimate the distance that has to be covered on the average before turbulence of a given reference intensity will be met, but it defines the proportion of all air mileage, or of all time, containing turbulence of a given reference intensity".

The probabilities tentatively chosen for the light, moderate and severe atmospheric disturbances are 10^{-1}, 10^{-3}, and 10^{-5}, respectively. As pointed out in the preceding quote, however, the numerical values are necessarily global averages and bear no relationship to any particular flight. When considering terminal operations, for example, the probable winds vary from airfield to airfield and from month to month at any given airfield. The atmospheric disturbance model is at best an imprecise average, justifying some engineering approximations as discussed in the preceding section.

One critical atmospheric phenomenon that was omitted from MIL-F-8785B was wind and associated shears. A wind shear at altitude can be adequately represented by a discrete gust, however it was felt that some more fundamental representation was required to cover operation in the earth's boundary layer. For the specification two altitude regions are considered - a low altitude region from the ground to about 2000 ft and a medium/high altitude region above 2000 ft. The boundary between the two regions is not rigid but is more a function of the flight phase being considered. For the low altitude region a logarithmic wind profile with altitude is specified and the proposed revision to MIL-F-8785B also directs the consideration of wind vector shear, i.e. changes in wind direction with altitude.

Atmospheric stability has significant influences on the wind and turbulence characteristics (see, for example, References A-10 and A-11). The logarithmic wind profile specified herein is applicable to a neutral or slightly unstable atmosphere. The data presented in Figure A-1 (Reference A-12) indicate that this is consistent with surface wind speeds greater than approximately 10 kts. Higher wind speeds enhance the atmospheric mixing and support the near neutral stability. Figure A-1 also shows that near neutral stability (i.e. categories C and D) and hence, by implication, the wind profile proposed for the revision to MIL-F-8785B occurs with approximately 55% probability. The proposed revision apparently neglects atmospheric conditions with a total probability of occurrence of about 45%. What is especially unfortunate is that these extreme, or less probable, atmospheric conditions probably cause more than their fair share of aircraft accidents and should not be neglected.

Unstable conditions caused by the onset of strong surface heating are normally associated with light wind speeds. These conditions often cause significant fluctuations in wind direction and the production of thermals, depending on the terrain. Changes in wind direction with altitude are believed to be of sufficient importance that they are suggested in the proposed revision, even though the probability of occurrence is less in neutral stability. Phenomena such as thermals can be adequately represented as discrete gusts.

Stable atmospheric conditions are often associated with strong temperature inversions. A strong inversion has the ability to make conditions above and below it independent of each other. There is the possibility of significant changes in wind speed and/or direction across the inversion. Again this type of disturbance can conveniently be represented by discrete gusts.

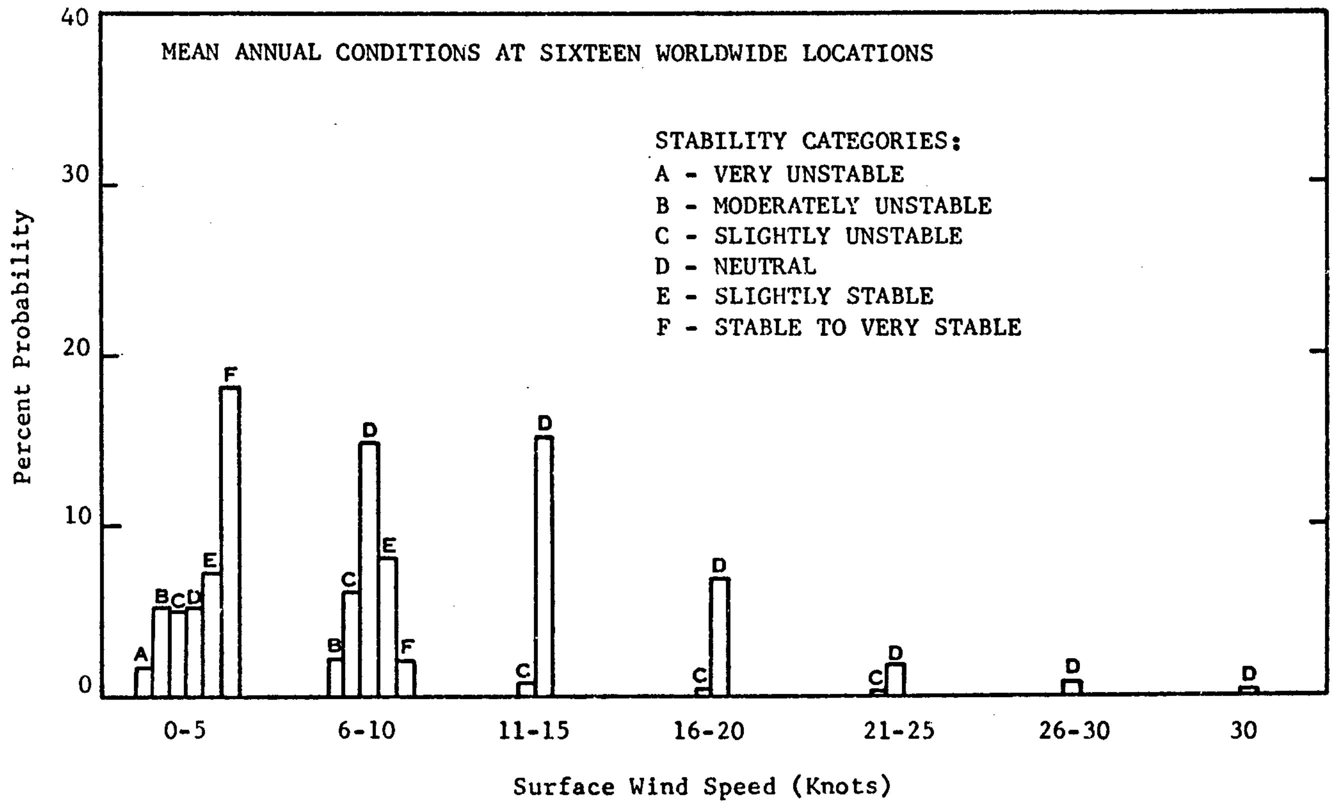


Figure A-1. Joint Percent Probabilities of Surface Wind Speed and Stability Categories

The proposed changes to MIL-F-8785B will now be discussed paragraph by paragraph. The current paragraph is listed first, then the proposed revision followed by the rationale for the change.

III. PROPOSED REVISION TO MIL-F-8785B

MIL-F-8785B paragraph:

3.3.7 Lateral-directional control in cross winds. It shall be possible to take off and land with normal pilot skill and technique in 90-degree cross winds, from either side, of velocities up to those specified in Table XI, etc.

Revised paragraph:

3.3.7 Lateral-directional control in cross winds. It shall be possible to take off and land with normal pilot skill and technique in 90-degree cross winds, from either side, of velocities up to those specified in Table XI with a wind profile as specified in Section 3.7.4.2, etc.

Rationale for revision:

This requirement is changed to include wind shear, which is believed to be a primary item in the piloting task. It is recognized to be critical in landing more than take-off.

MIL-F-8785B paragraphs:

3.7 Atmospheric Distrubances

3.7.1 Use of Turbulence Models. Paragraphs 3.7.2 through 3.7.5 specify a continuous random turbulence model and a discrete turbulence model that shall be used in analysis to determine compliance with those requirements of this Specification that refer to 3.7 explicitly, to assess:

a. The effect of turbulence on the flying qualities of the airplane;

b. The ability of a pilot to recover from the effects of discrete gusts.

Revised paragraph:

3.7 Atmospheric Distrubances

3.7.1 Use of Environmental Models. Paragraphs 3.7.2 through 3.7.5 specify models of wind shear, continuous random turbulence and discrete gusts that shall be used in analyses to determine compliance with those requirements of this Specification that refer to 3.7 explicitly, to assess:

a. The effects of certain environmental conditions on the flying qualities of the airplane;

b. The ability of a pilot to recover from upsets caused by environmental conditions.

For the purposes of this Specification the atmosphere shall be considered to consist of two regions, low altitude (ground level to approximately 2000 ft) and med/high altitude (above approximately 2000 ft). The low altitude model shall apply to Category C and any other Flight Phase (e.g. ground attack, terrain following) designated by the procuring activity. The med/high altitude model is intended to apply to those Flight Phases where proximity to the ground is not a factor, generally Categories A and B. In application it will be permissible to use conditions at an average altitude for the med/high altitude model only.
Rationale for revision:
The changes reflect the introduction of a model specifically for low altitudes, including wind shears. In practice, the boundary between the two regions does not need to be rigid, 2000 ft is a convenient number.

MIL-F-8785B paragraph:

3.7.2 Turbulence models. Where feasible, the von Karman form shall be used for the continuous random turbulence model, so that the flying qualities analyses will be consistent with the comparable structural analyses. When no comparable structural analysis is performed or when it is not feasible to use the von Karman form, use of the Dryden form will be permissible. In general, both the continuous random model and the discrete model shall be used. The scale and intensities used in determining the gust magnitudes for the discrete model shall be the same as those used in the Dryden continuous random model.

Revised paragraph:

3.7.2. Med/high altitude environmental model. Same as above.

Rationale for revision:

Change in title. In addition, the terms "turbulence" or "turbulence model" will only apply to the random, continuous disturbances and the term "gust" will only apply to discrete disturbances.

MIL-F-8785B paragraph:

3.7.2.1 Continuous random model (von Karman form). The von Karman form of the spectra for the turbulence velocities is:

$$\Phi_{u_g}(\Omega) = \sigma_u^2 \frac{2\,Lu}{\pi} \frac{1}{[1 + (1.399\, L_u \Omega)^2]^{5/6}}$$

$$\Phi_{v_g}(\Omega) = \sigma_v^2 \frac{Lv}{\pi} \frac{1 + 8/3(1.339\, Lv\Omega)^2}{[1 + (1.339\, L_v \Omega)^2]^{11/6}}$$

$$\Phi_{w_g}(\Omega) = \sigma_w^2 \frac{Lw}{\pi} \frac{1 + 8/3(1.339\, Lw\Omega)^2}{[1 + (1.339\, L_w \Omega)^2]^{11/6}}$$

3.7.2.2 Continuous random model (Dryden form). The Dryden form of the spectra for the turbulence velocities is:

$$\Phi_{u_g}(\Omega) = \sigma_u^2 \frac{2\,Lu}{\pi} \frac{1}{1 + (L_u \Omega)^2}$$

$$\Phi_{v_g}(\Omega) = \sigma_v^2 \frac{Lv}{\pi} \frac{1 + 3\,(Lv\,\Omega)^2}{[1 + (L_v\,\Omega)^2]^2}$$

$$\Phi_{w_g}(\Omega) = \sigma_w^2 \frac{Lw}{\pi} \frac{1 + 3\,(Lw\,\Omega)^2}{[1 + (L_w\,\Omega)^2]^2}$$

Revised paragraphs:

3.7.2.1 Turbulence model (von Karman form). As above.

3.7.2.2 Turbulence model (Dryden form). As above

Rationale for revision: Change in titles only, to be consistent.

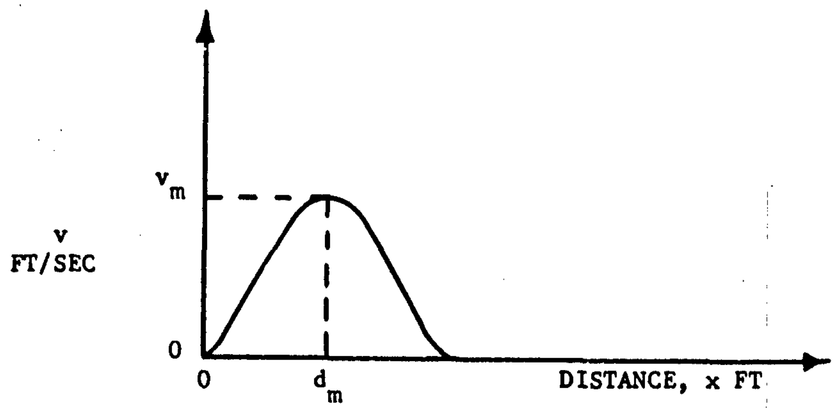
MIL-F-8785B paragraph:

3.7.2.3 Discrete model. The discrete turbulence model may be used for any of the three gust-velocity components. The discrete gust has the "1 - cosine" shape:

$$v = 0 \qquad , x < 0$$

$$= \frac{v_m}{2} \left(1 - \cos \frac{\pi x}{d_m}\right) \qquad , 0 \leq x \leq 2d_m$$

$$= 0 \qquad , x > 2d_m$$



Several values of d_m shall be used, each chosen so that the gust is tuned to each of the natural frequencies of the airplane and its flight control system (higher-frequency structural modes may be excepted). The magnitude v_m shall then be chosen from Figure A-2. The parameters L and σ to be used with Figure A-2 are the Dryden scales and intensities from 3.7.3 or 3.7.4 for the velocity component under consideration.

Revised paragraph:

3.7.2.3 Discrete gust model. The discrete gust model may be used for any of the three gust-velocity components and, by derivation, any of the three angular components.

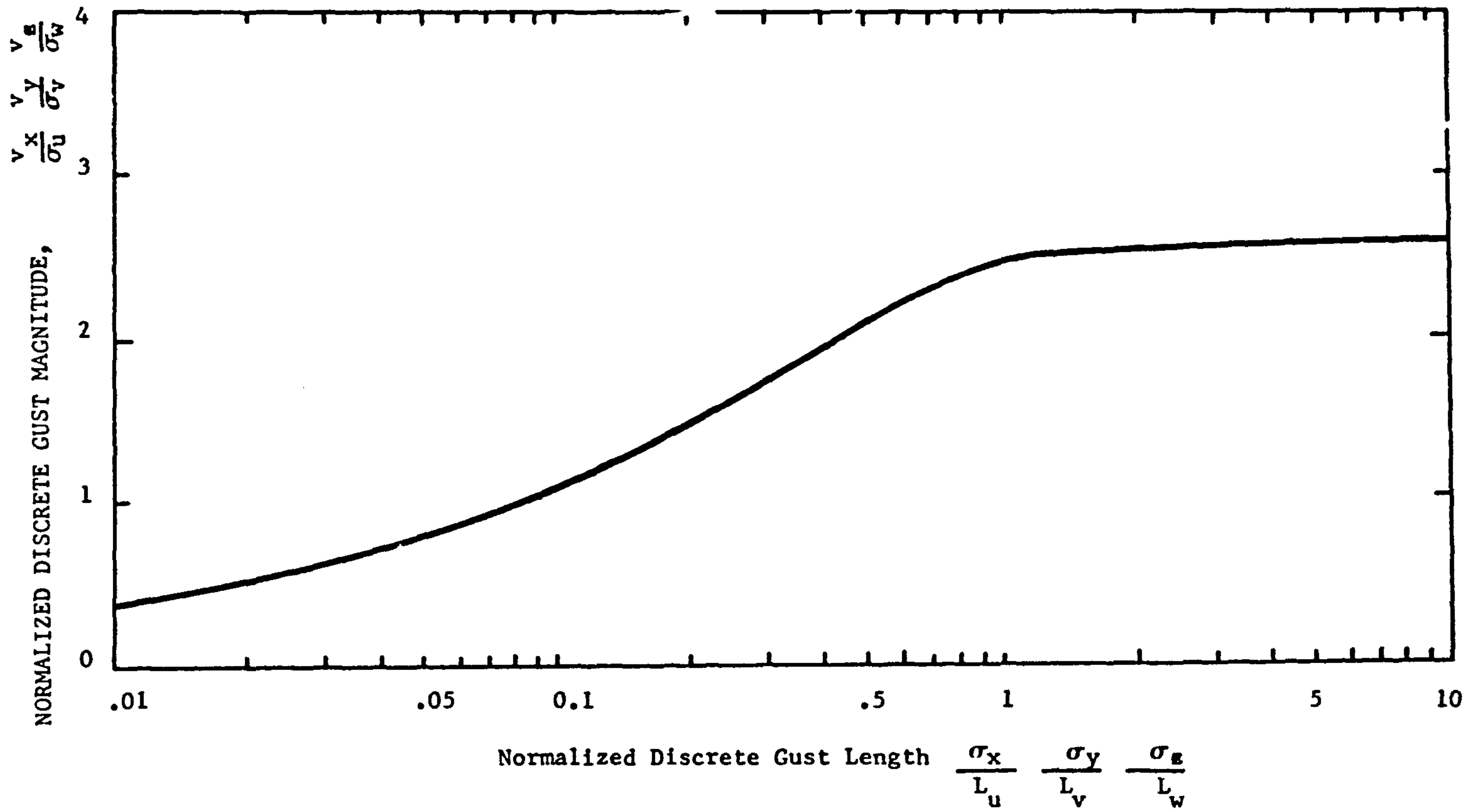


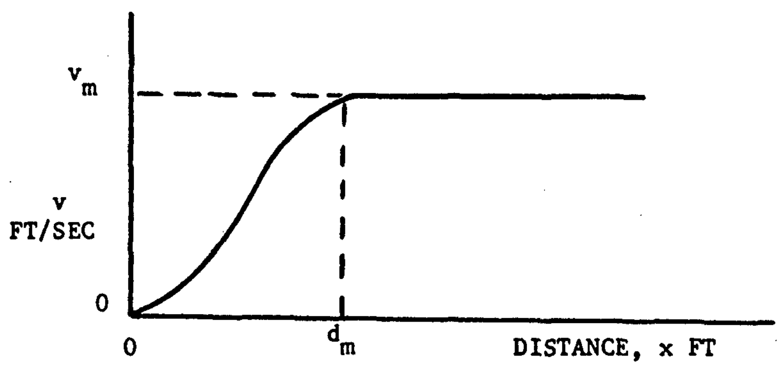
Figure A-2. Magnitude of Discrete Gusts

A suggested discrete gust has the "1 - cosine" shape given by:

$$v = 0 \qquad , x < 0$$

$$v = \frac{v_m}{2}\left(1 - \cos \frac{\pi x}{d_m}\right) \qquad , 0 \leq x \leq d_m$$

$$v = v_m \qquad , x > d_m$$



The discrete gust above may be used singly or in multiples in order to assess airplane response to, or pilot control of, large disturbances. Step function or linear ramp gusts may also be used.

Rationale for revision:

The term "gust" replaces "turbulence" and the length and magnitude are in the "scales and intensities" paragraph. In addition, only half of the 1 - cosine period is specified in order to provide more flexibility in application. A single gust can now represent a discrete wind shear, for instance. The new specification will also provide for the use of pairs of gusts which may, or may not, be equal and opposite in magnitude, and therefore includes, but is not limited to, the discrete turbulence model given in MIL-F-8785B.

MIL-F-8785B paragraph:

3.7.3 Scale and intensities (clear air turbulence). The root-mean-square intensity σ_w for clear air turbulence is defined on Figure A-3 as a function of altitude. The intensities σ_u and σ_v may be obtained using the relationships.

$$\frac{\sigma_u^2}{L_u^{2/3}} = \frac{\sigma_v^2}{L_v^{2/3}} = \frac{\sigma_w^2}{L_w^{2/3}} \qquad \text{(von Karman form)}$$

$$\frac{\sigma_u^2}{L_u} = \frac{\sigma_v^2}{L_v} = \frac{\sigma_w^2}{L_w} \qquad \text{(Dryden form)}$$

The scales for clear air turbulence are defined in 3.7.3.1 and 3.7.3.2 as a function of altitude. The altitude shall be defined consistently with any applicable terrain models specified in the contract. For those Flight Phases involving climbs and descents, a single set of scale and intensities based on an average altitude may be used. If an average set of scales and intensities is used for Category C Flight Phases, it shall be based on an altitude of 500 feet.

3.7.3.1 Clear air turbulence (von Karman scales). The scales for clear air turbulence using the von Karman form are:

Above h = 2500 feet: $L_u = L_v = L_w = 2500$ feet

Below h = 2500 feet: $L_w = h$ feet

$L_u = L_v = 184\ h^{1/3}$ feet

3.7.3.2 Clear air turbulence (Dryden scales). The scales for clear air turbulence using the Dryden form are:

Above h - 1750 feet: $L_u = L_v = L_w = 1750$ feet

Below h = 1750 feet: $L_w = h$ feet

$L_u = L_v = 145\ h^{1/3}$ feet

3.7.4 Scales and intensities (thunderstorm turbulence). The root-mean-square intensities σ_u, σ_v, and σ_w are all equal to 21 feet per second for thunderstorm turbulence. The scales for thunderstorm turbulence are defined in 3.7.4.1 and 3.7.4.2. These values are to be used when evaluating the airplane's controllability in severe turbulence, but need not be considered for altitudes above 40,000 feet.

3.7.4.1 Thunderstorm turbulence (von Karman scale). The scales for thunderstorm turbulence using the von Karman form are $L_u = L_v = L_w = 2500$ feet.

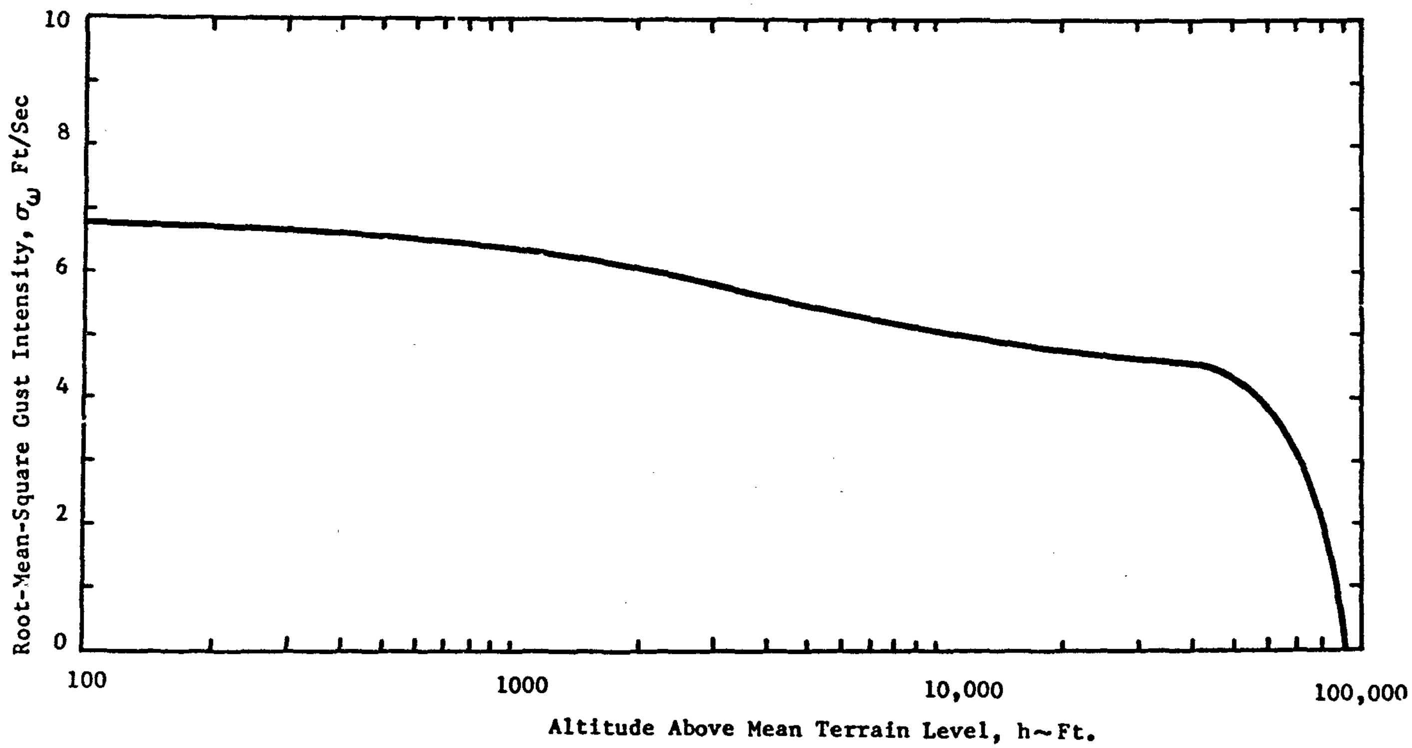


Figure A-3. Intensity for Clear Air Turbulence

3.7.4.2 Thunderstorm turbulence (Dryden scales). The scales for thunderstorm turbulence using the Dryden form are $L_u = L_v = L_w = 1750$ feet.

Revised paragraphs:

3.7.3 Scales and intensities (med/high altitude model)

The scales and intensities are based on the assumption that turbulence above 2000 feet is isotropic. Then

$$\sigma_u = \sigma_v = \sigma_w$$

$$\text{and} \qquad L_u = L_v = L_w$$

3.7.3.1 Turbulence scale lengths. The scales to be used are $L_u = L_v = L_w = 2500$ ft using the von Karman form or $L_u = L_v = L_w = 1750$ ft using the Dryden form.

3.7.3.2 Turbulence intensities. The root-mean-square turbulence intensities are given in Figure A-4 as functions of altitude for three levels of turbulence.

3.7.3.3 Gust lengths. Several values of d_m shall be used, each chosen so that the gust is tuned to each of the natural frequencies of the airplane and its flight control system (higher - frequency structural modes may be excepted). For the severe intensities, modes with wave lengths less than the turbulence scale length may be excepted.

3.7.3.4 Gust Magnitudes. The light and moderate gust magnitudes shall be determined from Figure A-5 and the appropriate curves of Figure A-4. Severe gust magnitude shall be:

a. 66 ft/sec EAS at V_G

b. 50 ft/sec EAS at V_H

c. 25 ft/sec EAS at V_L

d. 50 ft/sec EAS at speeds up to V_{LF} for the landing approach with the landing gear and other devices which are open or extended in their maximum open or maximum extended positions.

e. For altitudes above 20,000 ft the gust magnitudes may be reduced linearly from:

   (1) 66 ft/sec EAS at 20,000 ft to 38 ft/sec EAS at 50,000 ft for the V_G condition

   (2) 50 ft/sec EAS at 20,000 ft to 25 ft/sec EAS at 50,000 ft for the V_H condition

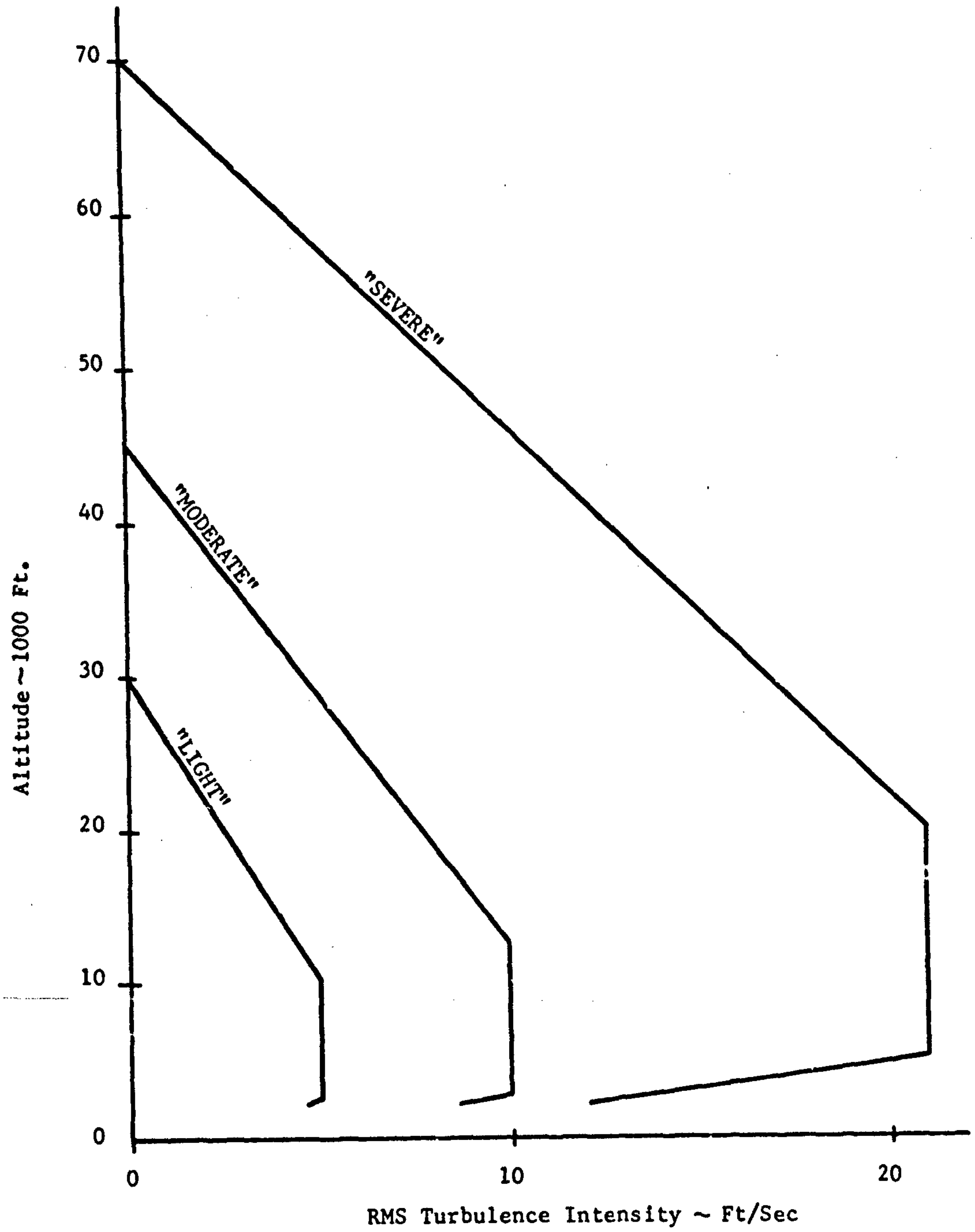


Figure A-4. Med/High Altitude Turbulence Intensity

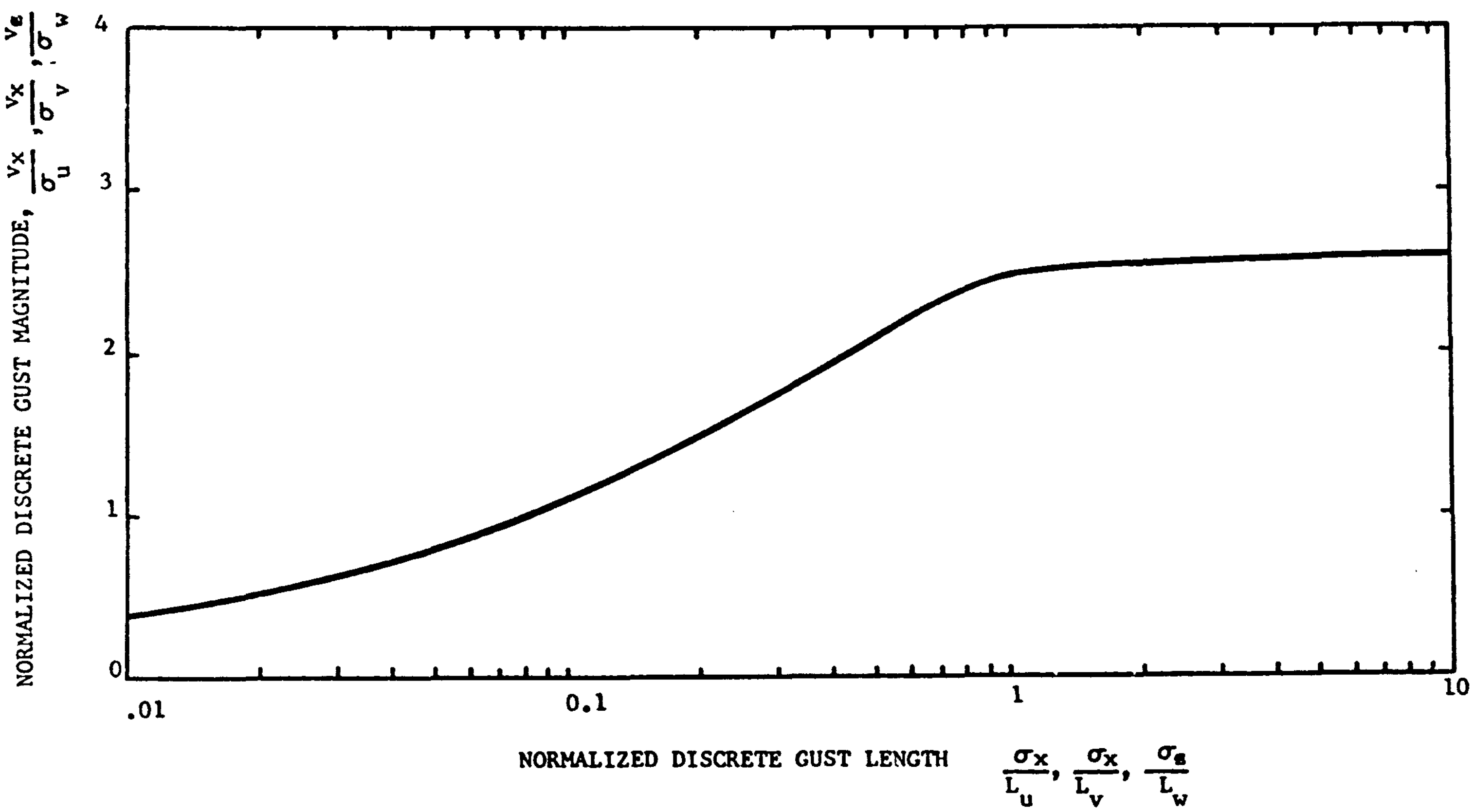


Figure A-5. Magnitude of Discrete Gusts

(3) 25 ft/sec EAS at 20,000 ft to 12.5 ft/sec EAS at 50,000 for the V_L condition.

f. For altitudes above 50,000 ft the specified equivalent gust velocity shall be multiplied by the factor

$$\sqrt{\sigma_{altitude}} \Big/ \sqrt{\sigma_{50000}} \qquad \text{where } \sigma = \rho/\rho_o$$

Rationale for revision:

While retaining a disturbance model similar to that in MIL-F-8785B it is now proposed to recognize the degradation in flying qualities as the turbulence intensity increases. The flying qualities requirements currently specified were developed assuming moderate turbulence, so they should apply in calm air or light disturbances. It is also recognized that there probably is no distinct point where the flying qualities suddenly degrade to another level. Currently the Air Force designs the structure to withstand certain gust loads but does not require that the pilot retain control of the aircraft (with some reasonable probability). This requirement belatedly recognizes the result of the celebrated "jet upsets" of the early 60's. The severe disturbance requirement could be waived for certain aircraft, such as Class I. More detailed rationale is contained in Section II. The RMS turbulence intensities are approximations to the curve given in MIL-F-9490. The severe gust magnitudes are taken from MIL-A-008861A. The wind profile specified is also consistent with that in MIL-F-9490.

MIL-F-8785B paragraph:

None.

Revised paragraph:

3.7.4 Low altitude environmental model. This section specifies the model of atmospheric disturbances to be used for all Category C operations. The effects of wind shear, turbulence and gusts may be analyzed separately. Some analysis and/or piloted simulation is required considering a complete environmental representation, demonstrating compliance with the requirements with the cumulative effects of wind shear, turbulence and gusts. A non-Gaussian turbulence representation together with a wind model may also be used to account for the gusts which appear in actual measured turbulence.

3.7.4.1 Wind speeds. The wind speed at 20 ft above the ground, U_{20} is given in Figure A-6 as a function of probability of occurrence. The values to be used for the different levels of atmospheric disturbance are indicated.

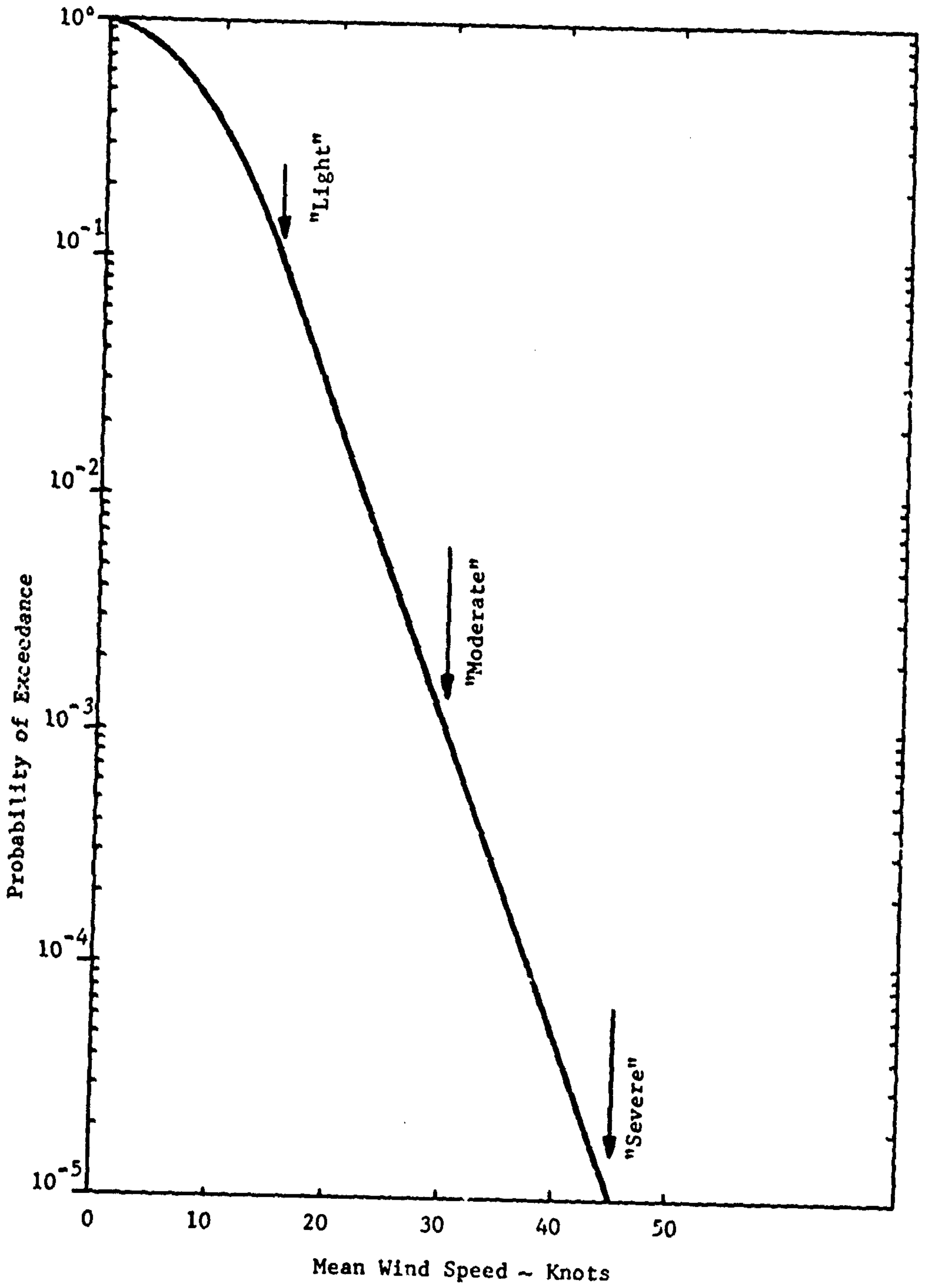


Figure A-6. Probability of Exceeding Mean Wind Speed at 20 Feet.

3.7.4.2 Wind shear. The magnitude of the wind scalar shear is defined by the use of the following expression for the mean wind profile as a function of altitude:

$$u_w = U_{20} \frac{\ell n\,(h/Zo)}{\ell n\,(20/Zo)}$$

where Zo = 0.15 ft for Category C Flight Phases

= 2.0 ft for other Flight Phases

3.7.4.3 Vector shear. Different orientations of the mean wind relative to the aircraft flight path or the runway shall be considered. In addition, changes in direction of the mean wind speed with altitude shall be considered, as given in Table A-1, using the most critical altitude and wind orientation.

TABLE A-1. VALUES OF WIND VECTOR SHEAR

DISTURBANCE	$\Delta \psi_w$	Δh, ft
Light	0	-
Moderate	90°	600
Severe	90°	300

Relative to the runway, values of U_{20} which give cross winds greater than the values in Section 3.3.7 or tailwinds greater than 10 knots need not be considered. At any altitude greater than 20 ft these limits do not apply.

3.7.4.4 Turbulence. The turbulence models of Sections 3.7.2.1 or 3.7.2.2 should be used. The appropriate scale lengths are given in Figure A-7 as functions of altitude. The turbulence intensities to be used are $\sigma_w = 0.1\ U_{20}$ and σ_u and σ_v are given by Figure A-8 as functions of σ_w and altitude.

3.7.4.5 Gusts. Discrete gusts of the form given in Section 3.7.2.3 shall be used, with both single and double ramps to be considered. Several values of d_m shall be used, each chosen so that the gust is tuned to each of the natural frequencies of the airplane and its flight control system. The gust magnitudes shall be determined from Figure A-5 using the appropriate values from Figures A-7 and A-8. The two halves of a double gust do not have to be the same length or magnitude.

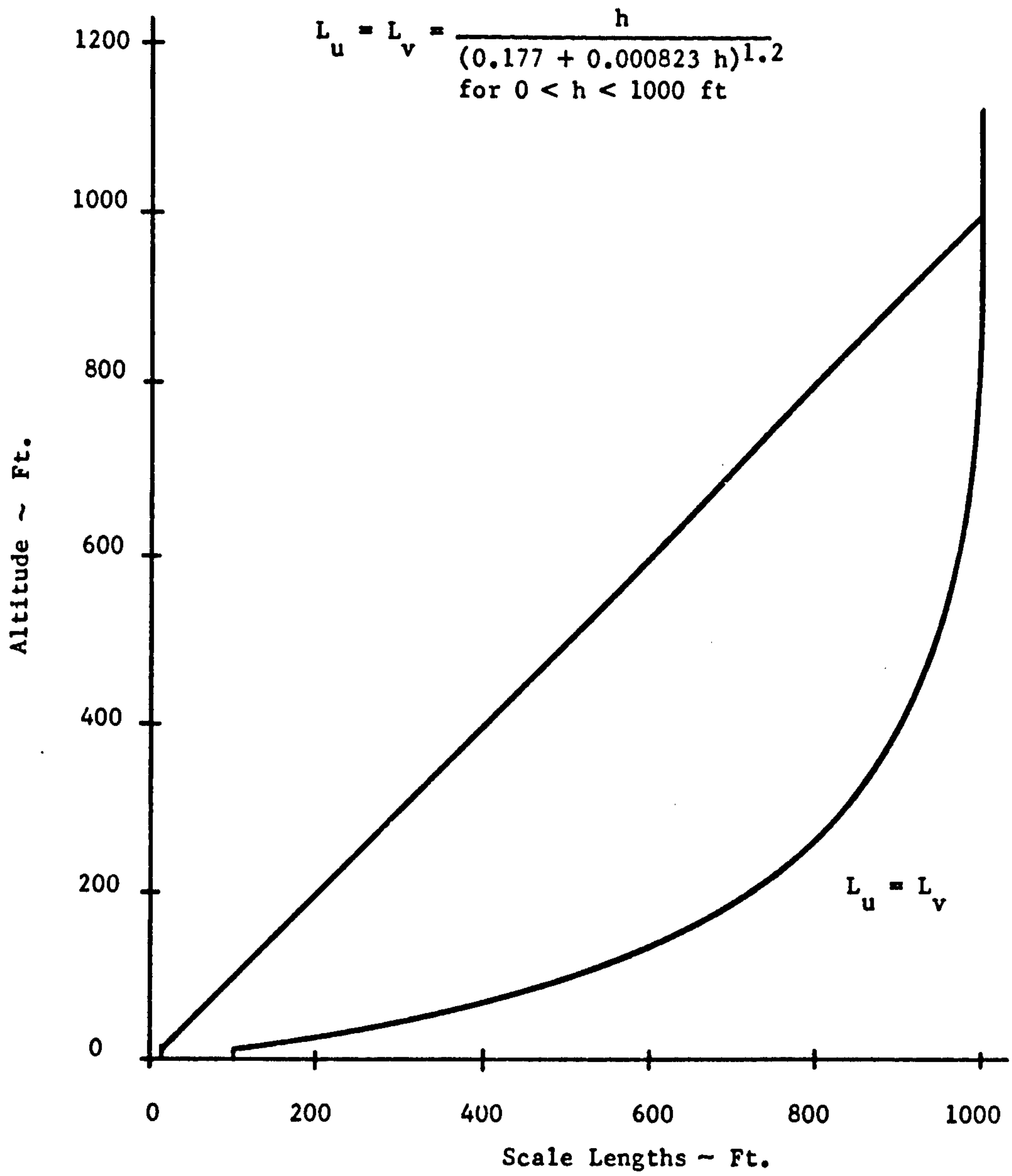


Figure A-7. Low Altitude Turbulence Integral Scales

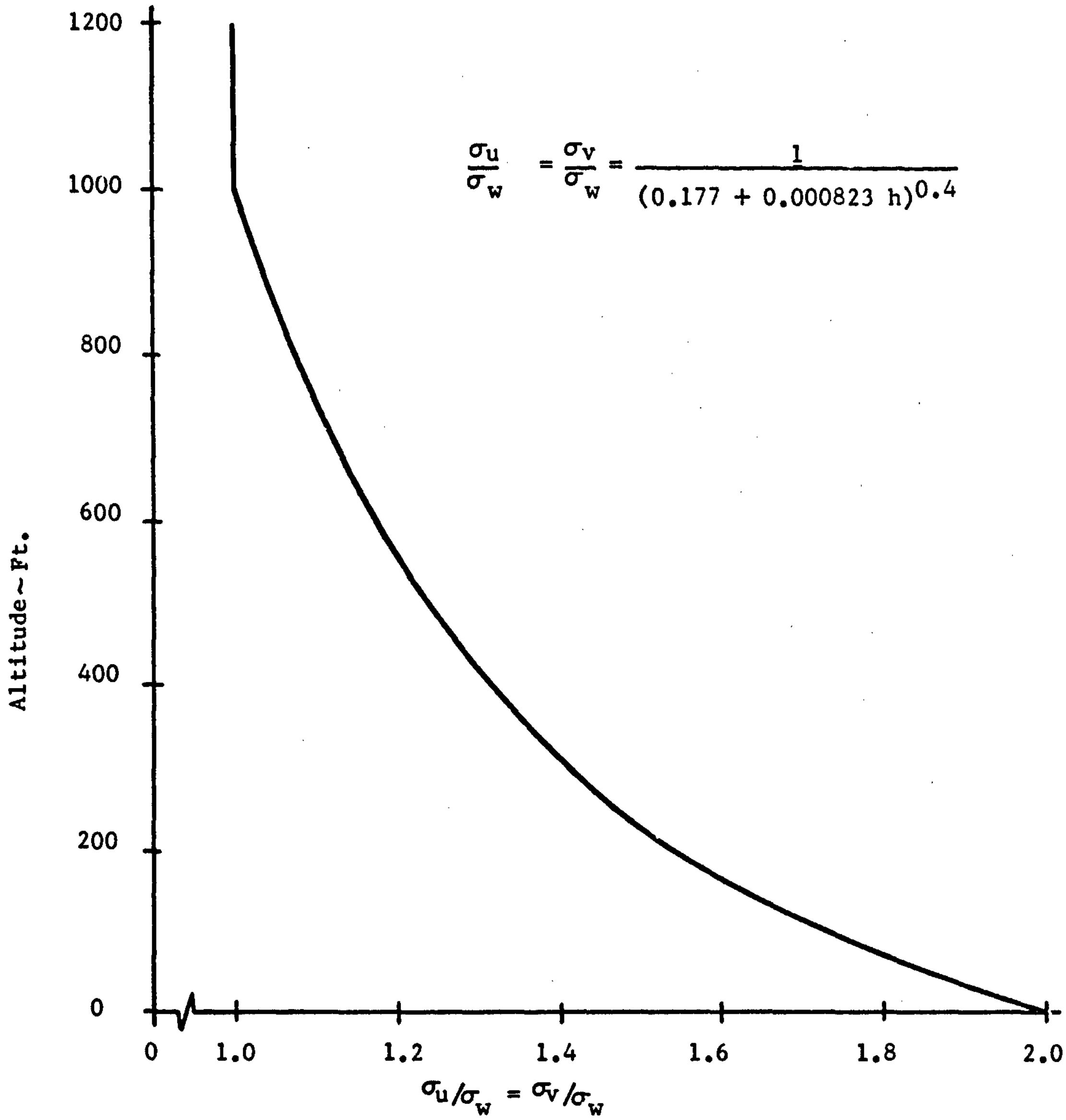


Figure A-8. Horizontal Turbulence RMS Intensities

Rationale for revision:

The inclusion of characteristics of the earth's boundary layer corrects a deficiency of MIL-F-8785B. A standard logarithmic wind profile has been chosen which corresponds to neutral atmospheric stability. Based on accident investigations such as Reference A-13, vector shear has been specified and it is assumed that extreme or unusual atmospheric phenomena can be represented by discrete gusts superimposed on the wind profile plus turbulence. The possibility of using a non-Gaussian turbulence representation is introduced but not required at present. Thus, the atmospheric disturbance model specified herein may be regarded as the minimum acceptable for demonstration of compliance. More sophisticated models will be encouraged.

MIL-F-8785B paragraph:

3.7.5 <u>Application of the turbulence models in analyses</u>. The gust velocities shall be applied to the airplane equations of motion through the aerodynamic terms only, and the direct effect of the gust on the aerodynamic sensors shall be included when such sensors are part of the airplane augmentation system. When using the discrete model, all significant aspects of the penetration of the gust by the airplane shall be incorporated in the analyses. Application of the continuous random model depends on the range of frequencies of concern in the analyses of the airframe. When structural modes are significant, the exact distribution of the gust velocities over the airframe should be considered. For this purpose, it is acceptable to consider u_g and v_g as being one-dimensional functions only of x, but w_g shall be considered two-dimensional, a function of both x and y, for the evaluation of aerodynamic forces and moments.

When structural modes are not significant, airframe rigid-body responses may be evaluated by considering uniform gust immersion along with linear gradients of the gust velocities. The uniform immersion is accounted for by u_g, v_g, and w_g defined at the airplane center of gravity. The angular velocities due to the turbulence are equivalent in effect to the airplane angular velocities. These angular velocities are defined (precisely at very low frequencies only) as follows:

$$p_g = \frac{-\partial w_g}{\partial y} \qquad \Phi_{p_g}(\Omega) = \frac{\sigma_w^2}{L_w} \frac{0.8\left(\frac{\pi L_w}{4b}\right)^{1/3}}{1+\left(\frac{4b}{\pi}\Omega\right)^2}$$

$$-\dot{\alpha}_g = q_g = \frac{\partial w_g}{\partial x} \qquad \Phi_{q_g}(\Omega) = \frac{\Omega^2}{1+\left(\frac{4b}{\pi}\Omega\right)^2}\Phi_{w_g}(\Omega)$$

$$r_g = \frac{-\partial v_g}{\partial x} \qquad \Phi_{r_g}(\Omega) = \frac{\Omega^2}{1+\left(\frac{3b}{\pi}\Omega\right)^2}\Phi_{v_g}(\Omega)$$

where b = wing span

The turbulence velocities u_g, v_g, w_g, p_g, q_g, and r_g are then applied to the airplane equations of motion through the aerodynamic terms. For longitudinal analyses u_g, w_g, and q_g gusts should be employed. For lateral-directional analyses v_g, p_g, and r_g should be used. The gust velocity components u_g, v_g, and w_g shall be considered mutually independent (uncorrelated) in a statistical sense. However, q_g is correlated with w_g, and r_g is correlated with v_g. The rolling velocity gust p_g is statistically independent of all the other gust components.

Revised paragraph:

3.7.5 Application of the environmental models in analyses. The gust and turbulence velocities shall be applied to the airplane equations of motion through the aerodynamic terms only, and the direct effect on the aerodynamic sensors shall be included when such sensors are part of the airplane augmentation system. When using the discrete gust model, all significant aspects of the penetration of the gust by the airplane shall be incorporated in the analyses. Application of the disturbance model depends on the range of frequencies of concern in the analyses of the airframe. When structural modes are significant, the exact distribution of the turbulence velocities should be considered. For this purpose, it is acceptable to consider u_g and v_g as being one-dimensional functions only of x, but w_g shall be considered two-dimensional, a function of both x and y, for the evaluation of aerodynamic forces and moments.

3.7.5.1 Med/high altitude model. When structural modes are not significant, airframe rigid-body responses may be evaluated by considering uniform gust or turbulence immersion along with linear gradients of the disturbance velocities. The uniform immersion is accounted for by u_g, v_g and w_g defined at the airplane center of gravity. The disturbances u_g, v_g and w_g may be taken in airplane body axes because of the assumed condition of isotropy. The angular velocities due to turbulence are equivalent in effect to airplane angular velocities. These angular velocities are defined (precisely at very low frequencies only) as follows:

$$p_g = \frac{-\partial w_g}{\partial y}$$

$$-\dot{\alpha} = q_g = \frac{\partial w_g}{\partial x}$$

$$r_g = \frac{-\partial v_g}{\partial x}$$

The spectra of the angular velocity disturbances due to turbulence are then given by:

$$\Phi_{p_g}(\Omega) = \frac{\sigma_w^2}{L_w} \frac{0.8\left(\frac{\pi L_w}{4b}\right)^{1/3}}{1 + \left(\frac{4b}{\pi}\Omega\right)^2}$$

$$\Phi_{q_g}(\Omega) = \frac{\Omega^2}{1 + \left(\frac{4b}{\pi}\Omega\right)^2} \Phi_{w_g}(\Omega)$$

$$\Phi_{r_g}(\Omega) = \frac{\Omega^2}{1 + \left(\frac{3b}{\pi}\Omega\right)^2} \Phi_{v_g}(\Omega)$$

The turbulence components u_g, v_g, w_g, and p_g shall be considered mutually independent (uncorrelated) in a statistical sense. However, q is correlated with w_g and r_g is correlated with v_g. For the discrete gusts the linear gradient gives angular velocity perturbations of the form:

$$P_g = P_m \sin\left(\frac{\pi x}{d_m}\right)$$

3.7.5.2 Low altitude model. The turbulence velocity components u_g, v_g and w_g are to be taken along axes with u_g aligned with the actual wind vector. It is permissible to use the form given in 3.7.5.1 for the angular velocity perturbations in airplane body axes.

Rationale for revision:

The major change is to specify that the turbulence velocity components are with respect to the wind. The angular velocity perturbations are retained in body axes because it is only an approximate treatment and the added complexity of determining the values as functions of heading is not justified. In fact, Reference A-14 indicates that the linear gradient derivation of the roll gusts is as much in error as neglecting the term.

IV. RESPONSE CRITERIA

It is felt that there is currently too little data to support specifications on response criteria. The proposed revision to the British flying qualities specification (Reference A-9) does include some response criteria and is, therefore, a starting point. It is also possible to postulate the possible form of other criteria which would require validation before inclusion in the specification, and these are discussed relative to the current paragraph in MIL-F-8785B.

Flight path stability (paragraph 3.2.1.3) Both References A-2 and A-9 have requirements for the rate of change of flight path angle with airspeed at constant throttle setting (although the numbers are not identical). Reference A-9 also comments that the values specified make sufficient allowance for the effects of at least moderate turbulence. Assuming that flight path/airspeed control becomes more difficult as the intensity of atmospheric disturbances increases the following form is suggested for the maximum value of rate of change of flight path angle with airspeed:

FLYING QUALITIES	ATMOSPHERIC DISTURBANCES		
	LIGHT	MODERATE	SEVERE
Level 1	0.06	-0.03	-0.12
Level 2	0.15	0.06	-0.03
Level 3	0.24	0.15	0.0

The numbers suggested for moderate and severe atmospheric disturbances are completely arbitrary, at present. It should be pointed out, however, that the sense of these requirements can be satisfied by increasing airspeed which is commonly done in adverse conditions. In application, therefore, this requirement would probably mean defining the approach speeds to be used in adverse conditions, rather than a "rule of thumb" of adding 50% of the wind or 50% of the reported gusts to the approach speed.

Short-period damping (MIL-F-8785B, paragraph 3.2.2.1.2). References A-2 and A-9 have similar requirements for short period damping ratio, which Reference A-9 states to be adequate for flight in severe turbulence. Both references allow a reduction in the Level 3 minimum damping ratio above 20,000 ft consistent with the reduction in the turbulence intensity with altitude. Possible revisions could be:

(i) Define the allowable reduction in minimum Level 3 short-period damping ratio with increasing altitude.

(ii) Allow a reduction in minimum Level 3 short-period damping ratio at speeds above the gust penetration speed, V_G, since the aircraft should not fly in severe turbulence at those speeds.

Currently it is not felt appropriate to include these changes because of insufficient data.

Pitch attitude deviations (no MIL-F-8785B paragraph). Reference A-9 indicates a possible closed loop criterion based on work reported in Reference A-15. This indicates that the RMS pitch excursion should be less than 1 degree in severe turbulence for Level 1 pilot rating of a Class IV aircraft in Category A flight phase. It is also possible to postulate that a similar requirement on RMS flight path excursions would exist for Category C flight phase. The work in Reference A-15 concerns analytical closed loop response prediction using a pilot model. Any requirements stated in terms of maximum RMS excursions would be applicable to analytical open or closed-loop analysis rather than piloted simulation. At present it is believed that there is insufficient data to support this type of requirement. The results of any such analysis would be a useful supplement to data presented to show compliance with the requirements.

Lateral-directional oscillations (Dutch roll) (MIL-F-8785B, paragraph 3.3.1.1). The current requirements are presumed to be adequate for moderate turbulence. Reference A-9 also increases the minimum allowable Dutch Roll damping for aircraft designed to operate in severe turbulence.

Roll mode (MIL-F-8785B, paragraph 3.3.12). The specified maximum roll-mode time constants were presumably developed to apply in at least some turbulence. Reference A-9 uses the same values as Reference A-2 but qualifies the requirement based on the parameter $1/V\omega_D \left| \phi/\beta \right|_D$. No substantiation is presented, but it would be a possible area of research.

Lateral-directional response to atmospheric disturbances. (MIL-F-8785B, paragraph 3.3.2.1). Reference A-2 requires "that the airplane will have acceptable response and controllability characteristics in atmospheric disturbances". It is still not possible to define the acceptable open-loop response and controllability characteristics in different levels and forms of atmospheric disturbance. A slight improvement is made by recognizing the progressive degradation of flying qualities due to increasing turbulence intensity.

Bank angle oscillations (MIL-F-8785B, paragraph 3.3.2.3). MIL-F-8785B currently only includes a requirement on ϕ_{OSC}/ϕ_{AV}. Reference A-9 includes possible open and closed-loop criteria for RMS bank oscillations due to turbulence. The closed loop criterion again based on Reference A-15 indicates that the RMS bank angle excursions should be less than 2.7° in severe turbulence for Level 1 pilot rating of a Class IV aircraft in Category A flight phase. The open-loop criterion is for landing approach based on a simulation to be reported. No specification is suggested at present.

Sideslip excursions (MIL-F-8785B, paragraph 3.3.2.4). Similar to the preceding discussion, RMS sideslip excursion due to turbulence is a possible criterion but no specification is suggested at present.

V. REFERENCES

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